Accelerator Physics Group activities at the APS

K. Harkay, ANL/APS

Seminar at ALS

2003 January 8

Accelerator and FEL Physics Group members

Katherine Harkay – Group leader

John Lewellen – Deputy group leader

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Yuelin Li

Vadim Sajaev

Lee Teng

Chun-xi Wang

Marion White (presently at SNS/ORNL)

Stephen Milton (former Group leader)

Acknowledgements

For more information, please visit the group home page:

http://www.aps.anl.gov/asd/physics/

We would like to recognize the many contributions of our APS colleagues:

Former members of Accelerator Physics Group: Stephen Milton (now APS/LCLS project head), Zhirong Huang (now at SLAC), Eliane Lessner (now at RIA/ANL), Ed Crosbie (retired), Sun-Bin Song (former postdoc)

Accelerator Operations Division: Glenn Decker

Operations Analysis Group: Michael Borland, Louis Emery, Nick Sereno

http://www.aps.anl.gov/asd/oag/oaghome.shtml

Diagnostics Group: Bingxin Yang, Alex Lumpkin, Xiang Sun

http://www.aps.anl.gov/asd/diagnostics/

Operations Group: Chih-Yuan Yao

RF Group: Ali Nassiri, Joshua Song

All others who contributed to the design and operation of the APS

Basic APS parameters

- 7 GeV
- Circumference 1104 m
- rf frequency 352 MHz (2.84 ns)
- h = 1296

A word on SR User operation

- Standard (~75%) ($\tau \sim$ 7-9 h)
  - 100 mA
  - Low emittance lattice (2.4 nm-rad)
  - 23 bunches spaced at h/24 (one missing) (4.3 mA/bunch)
  - Top-up
- Special operating modes (typ. 1-2 weeks ea. per run)
  - High emittance, non-top-up (7.7 nm-rad) ($\tau \sim$ 20 h)
  - Hybrid mode (1 or 3 + 56) ($\tau \sim$ 20 h)
  - Many-bunch mode (324 bunches) ($\tau \sim$ 100 h)

Overview

- Optics and machine characterization
  - Response matrix fit method
  - Model-independent analysis
- Impedance and collective effects
- Injector development
- FEL

Lattice development at the APS

Why we change the lattice:

- In order to improve the quality of the x-rays provided for the users
- Because we can do it – all quadrupoles at the APS storage ring have separate power supplies

- Initially, the lattice change was very difficult. The APS storage ring is a large machine containing 400 quadrupoles, 280 sextupoles, and 80 dipoles.
- The response matrix fit was applied to calibrate the linear model of the storage ring. The method is the same as used at NSLS and ALS (J. Safranek, D. Robin, and C. Steier helped during this work).

Orbit response matrix fit

- The orbit response matrix is the change in the orbit at the BPMs as a function of changes in steering magnets

$$\begin{pmatrix} x \\ y \end{pmatrix} = M_{\substack{measured \\ model}} \begin{pmatrix} \theta_x \\ \theta_x \end{pmatrix}$$

- The response matrix is defined by the linear lattice of the machine; therefore it can be used to calibrate the linear optics in a storage ring.
- Modern storage rings have a large number of steering magnets and precise BPMs, so measurement of the response matrix provides a very large array of precisely measured data.

Measurements and fitting

- APS has 320 steering magnets and 400 BPMs in each plane plus 400 quadrupoles and 280 sextupoles.
- For our measurements we use only 40 steering magnets in each plane to limit the size of the matrix and all BPMs. We do not vary sextupoles. The resulting response matrix has 32,000 elements, and the number of variables is 1320.
- Finally we solve the following equation (by iterations):

$$X = M^{-1} \cdot V$$

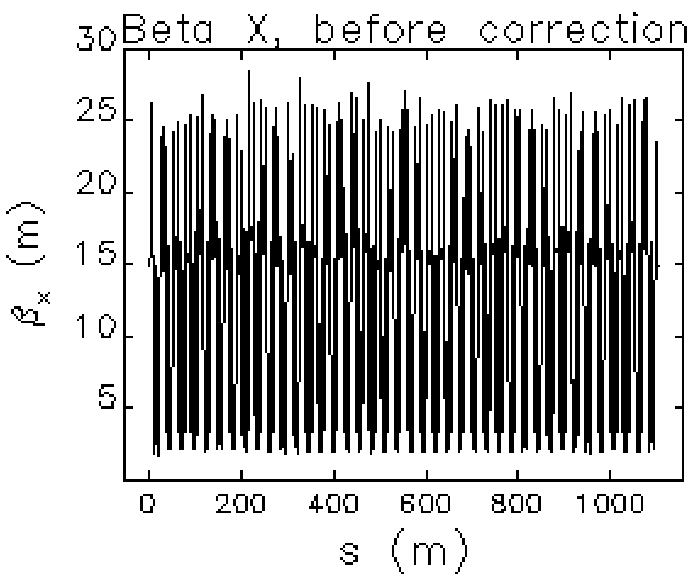
$$\begin{pmatrix} 1 \\ \times \\ 1320 \end{pmatrix} = \begin{pmatrix} 1320 \\ \times \\ 32000 \end{pmatrix} \cdot \begin{pmatrix} 1 \\ \times \\ 32000 \end{pmatrix}$$

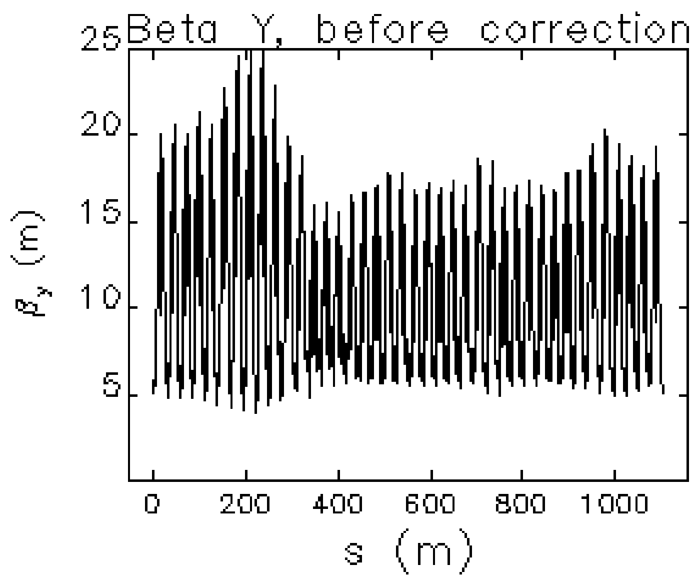
V. Sajaev

After the fit is done…

The result of the fit is the “parameter” file for `elegant` containing quadrupole errors, BPM gains, and corrector calibrations. This file represents the real model of the machine and can be used for different kinds of calculations in `elegant`.

Beta functions calculation (08/08/2001):





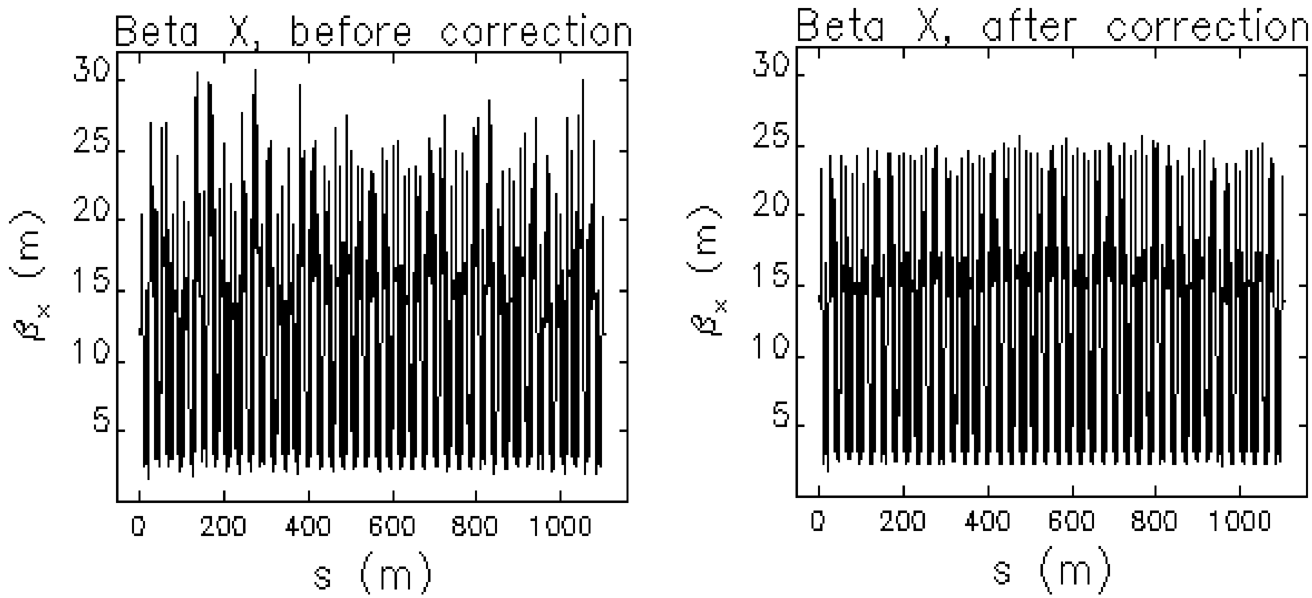
V. Sajaev

Exploitation of the model

- Improving the performance of the existing machine
  - Beta function correction - to improve lifetime, injection efficiency and to provide users with the radiation exactly as specified
  - BPM gain calibration
- Creation of new lattices
  - Increasing brightness of x-rays by decreasing the beam emittance
  - Exotic lattices:
    - Longitudinal injection to decrease beam motion during injection
    - Converging beta function to increase x-ray flux density

Beta function beating correction

Horizontal beta function for the low-emittance lattice before and after beta function correction (November 2001):



As a result of the correction, the lifetime increased from six hours to nine hours. The lifetime increase was crucial for top-up operation.

V. Sajaev

Creating new lattices

- Before the precise model of the APS storage ring was created, the process of creating a new lattice was taking many study shifts.
- Now it is possible to try a new lattice in just one shift. For example, the creation of the new “lower-emittance” lattice took only five shifts from scratch to user-available lattice (including beta function correction and user orbit restoration).

Increasing brightness of x-rays

- Brightness is the main single parameter characterizing a synchrotron light source. It is inversely proportional to the electron beam emittance.
- Over the last one and a half years, APS has made two big steps toward increasing the brightness:

Lattice: "High emittance" 7.7 nm×rad	→	Lattice: "Low emittance" 3.3 nm×rad 11/7/2001	→	Lattice: "Lower emittance" 2.4 nm×rad 10/15/2002

Response matrix fit allowed us to perform these changes quickly and ensured that the delivered beam parameters corresponded to the designed ones.

V. Sajaev

"Exotic lattices"

These lattices change just one sector but these changes are dramatic:

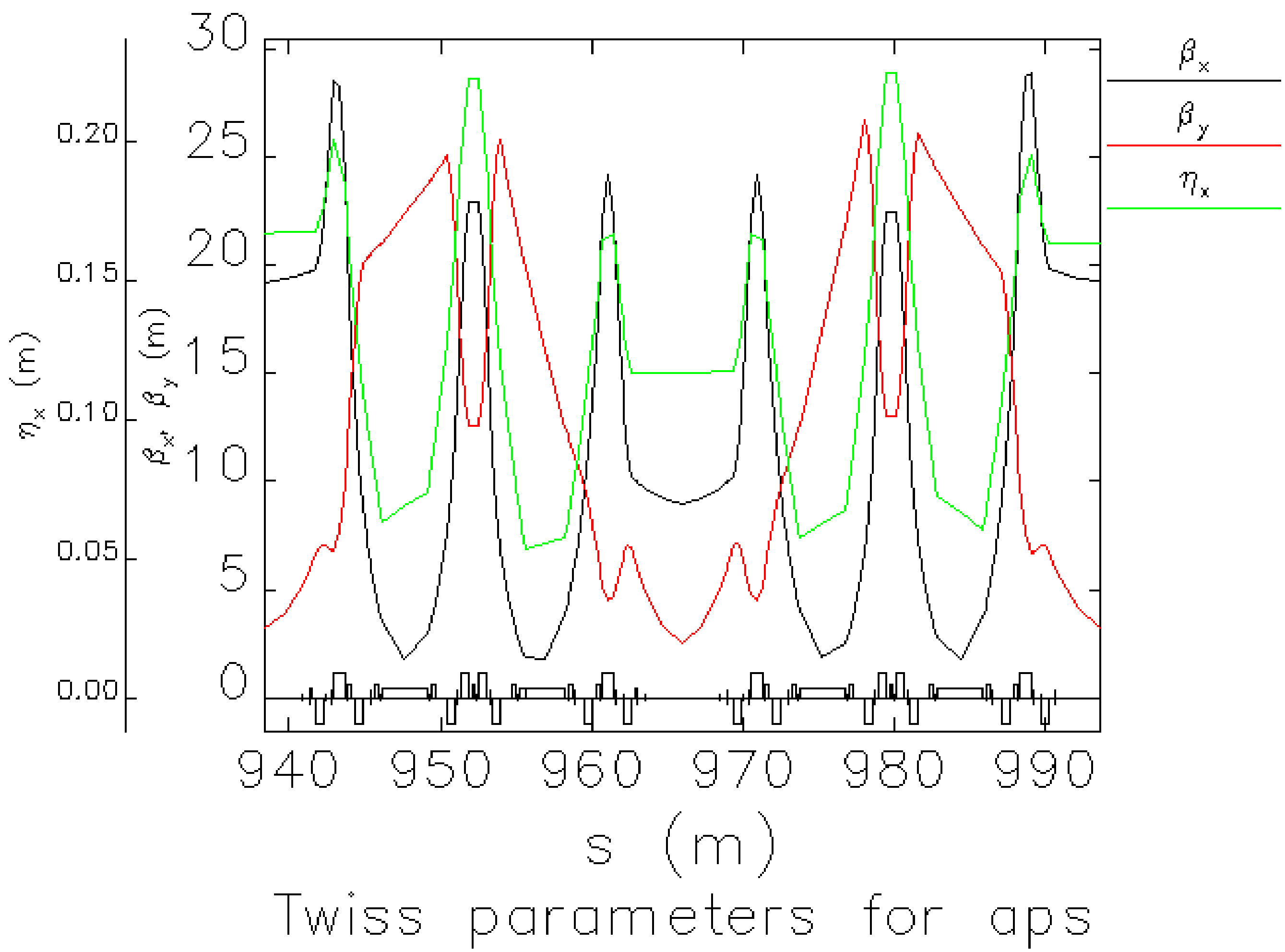
- ❑Longitudinal injection
- ❑Converging beta function
- ❑7-meter long ID straight section
- ❑Low horizontal beta ID straight section

All lattices were tested during studies. Some of them do little damage to the lifetime, some – not.

After the storage ring model is calibrated, the implementation of the new lattices becomes straightforward.

Low beta x lattice

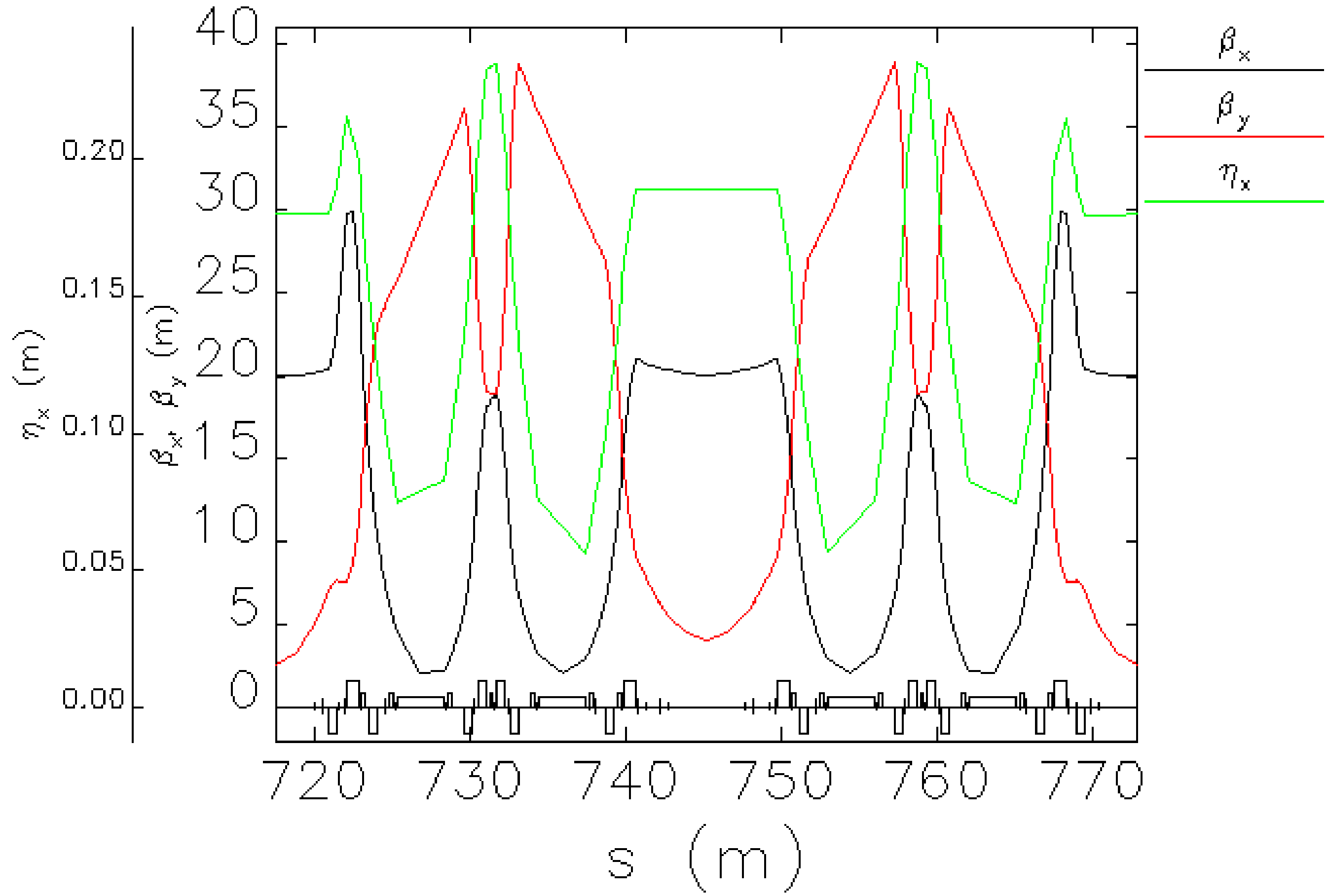
Beta X decreased from 19 m to 9 m. This was tested during studies successfully.



V. Sajaev

Missing Q1s lattice

Quads nearest to the ID are turned off. This will allow us to increase ID length from 5 m to 7 m.
This was tested during studies successfully.



Twiss parameters for aps

M. Borland

Model-Independent Analysis

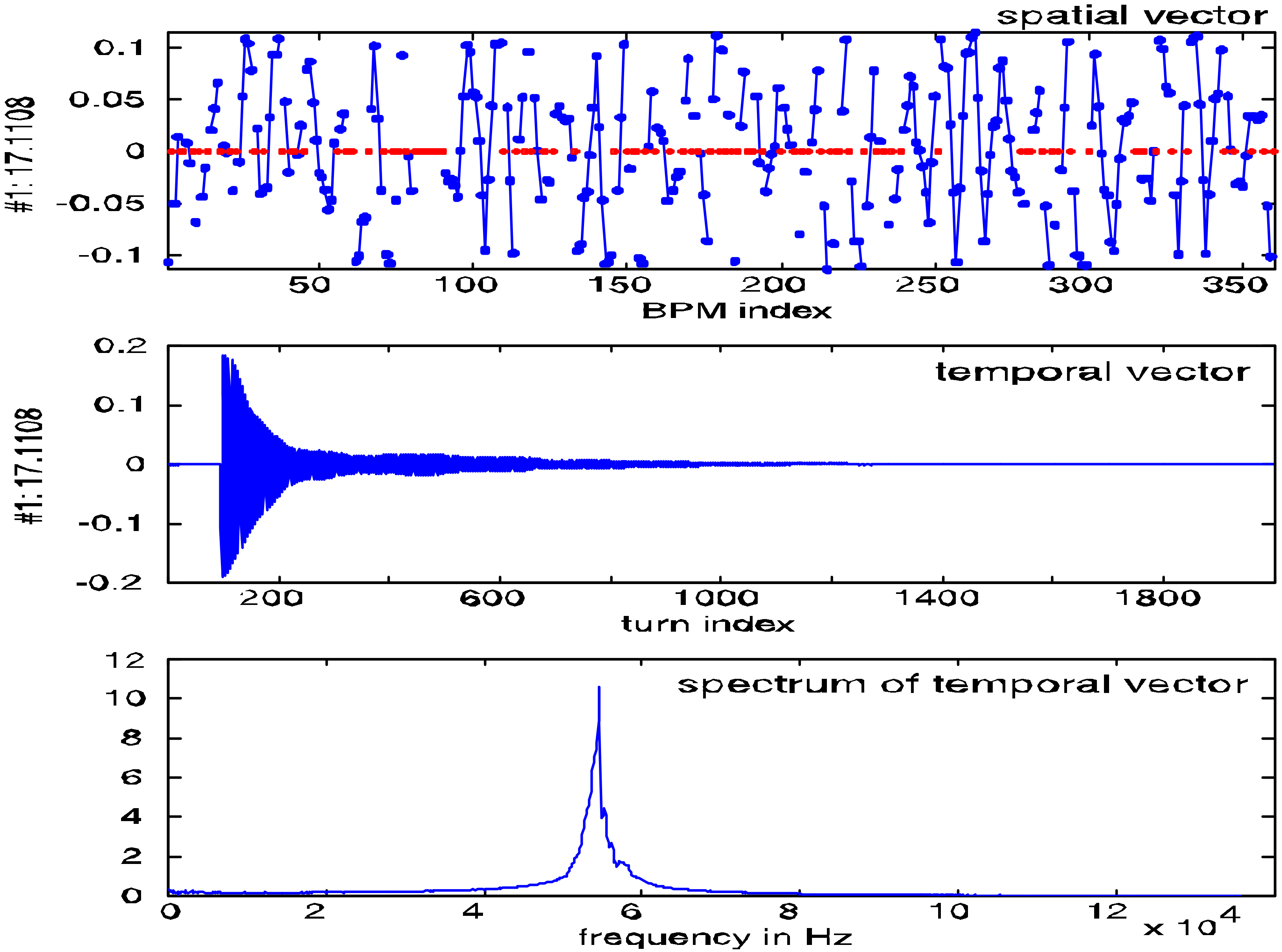
- MIA is a statistical analysis (principal composition analysis) of spatial-temporal modes in beam centroid motion recorded by the BPMs
- Mostly independent of detailed machine models
- Inclusive rather than exclusive – various other data analysis methods such as Fourier analysis, map analysis, etc. (even machine modeling) are being incorporated
- Not a recipe for a specific measurement, but rather a paradigm that facilitates systematic measurements and analysis of beam dynamics

Advantage: High sensitivity, model-independent, noninvasive, systematic

Basic requirement: A large set of reliable turn-by-turn BPM histories

Paper submitted to Phys Rev

C-X. Wang


spatial vector
#1: 17.1108
0.1
0.05
0
-0.05
-0.1
50
100
150
200
250
300
350
BPM index
temporal vector
#1: 17.1108
0.2
0.1
0
-0.1
-0.2
200
600
1000
1400
1800
turn index
spectrum of temporal vector
12
10
8
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4
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2
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6
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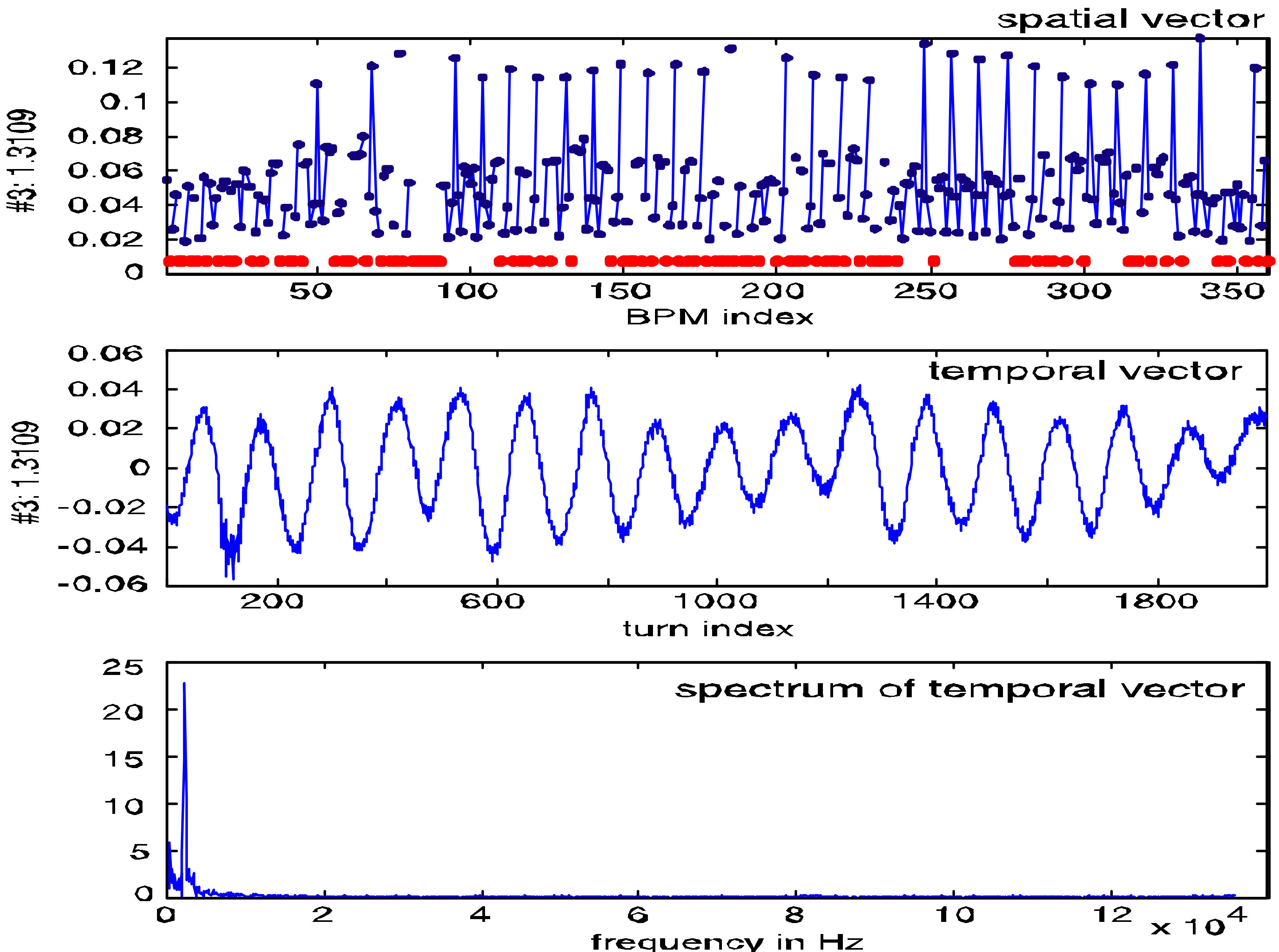
10
12
x 10^4
frequency in Hz

C-X. Wang


spatial vector
#3: 1.3109
0.12
0.1
0.08
0.06
0.04
0.02
0
50
100
150
200
250
300
350
BPM index
temporal vector
#3: 1.3109
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
200
600
1000
1400
1800
turn index
spectrum of temporal vector
25
20
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10
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6
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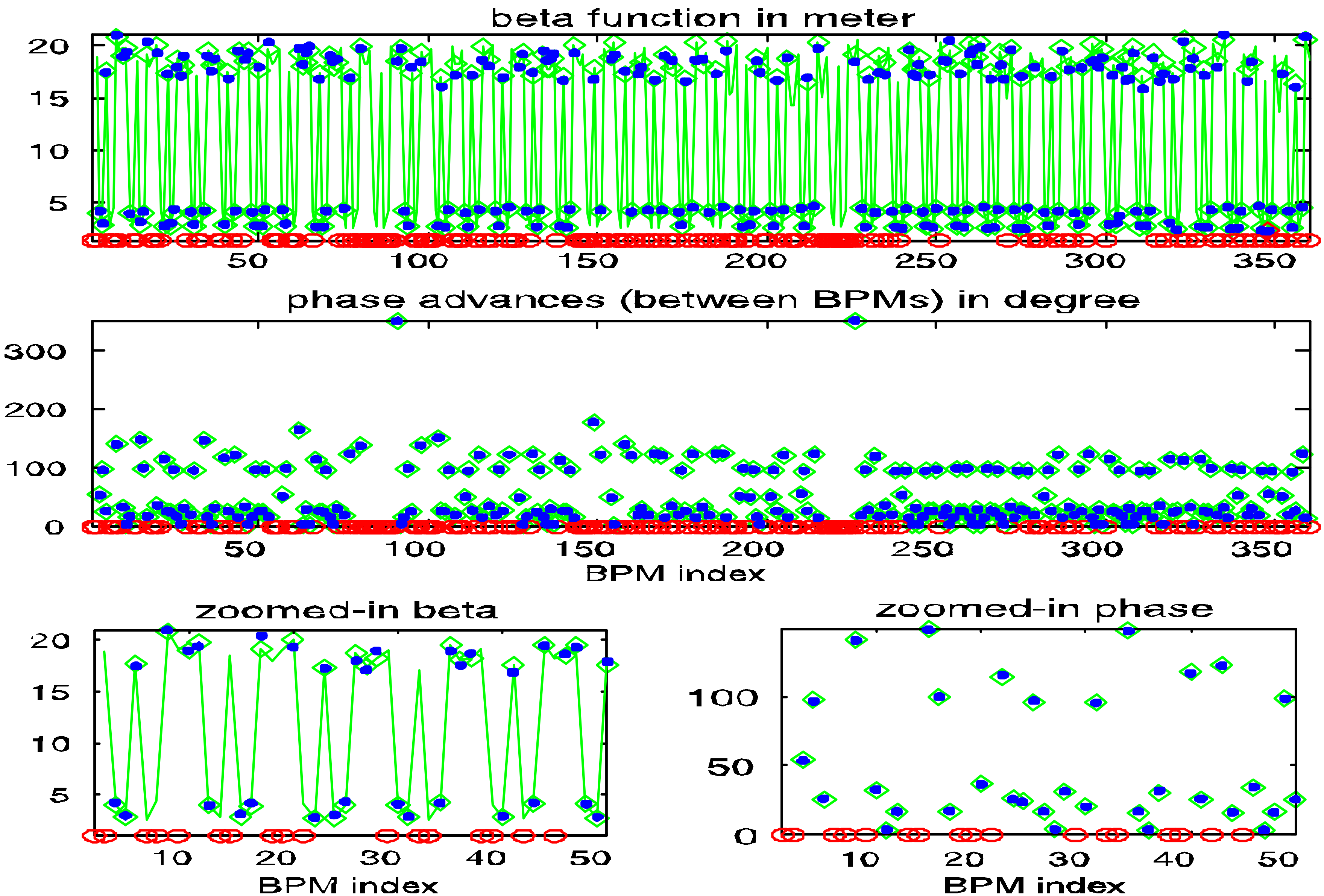
x 10^4
frequency in Hz

C-X. Wang


beta function in meter
20
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phase advances (between BPMs) in degree
300
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50
100
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200
250
300
350
BPM index
zoomed-in beta
20
15
10
5
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BPM index
zoomed-in phase
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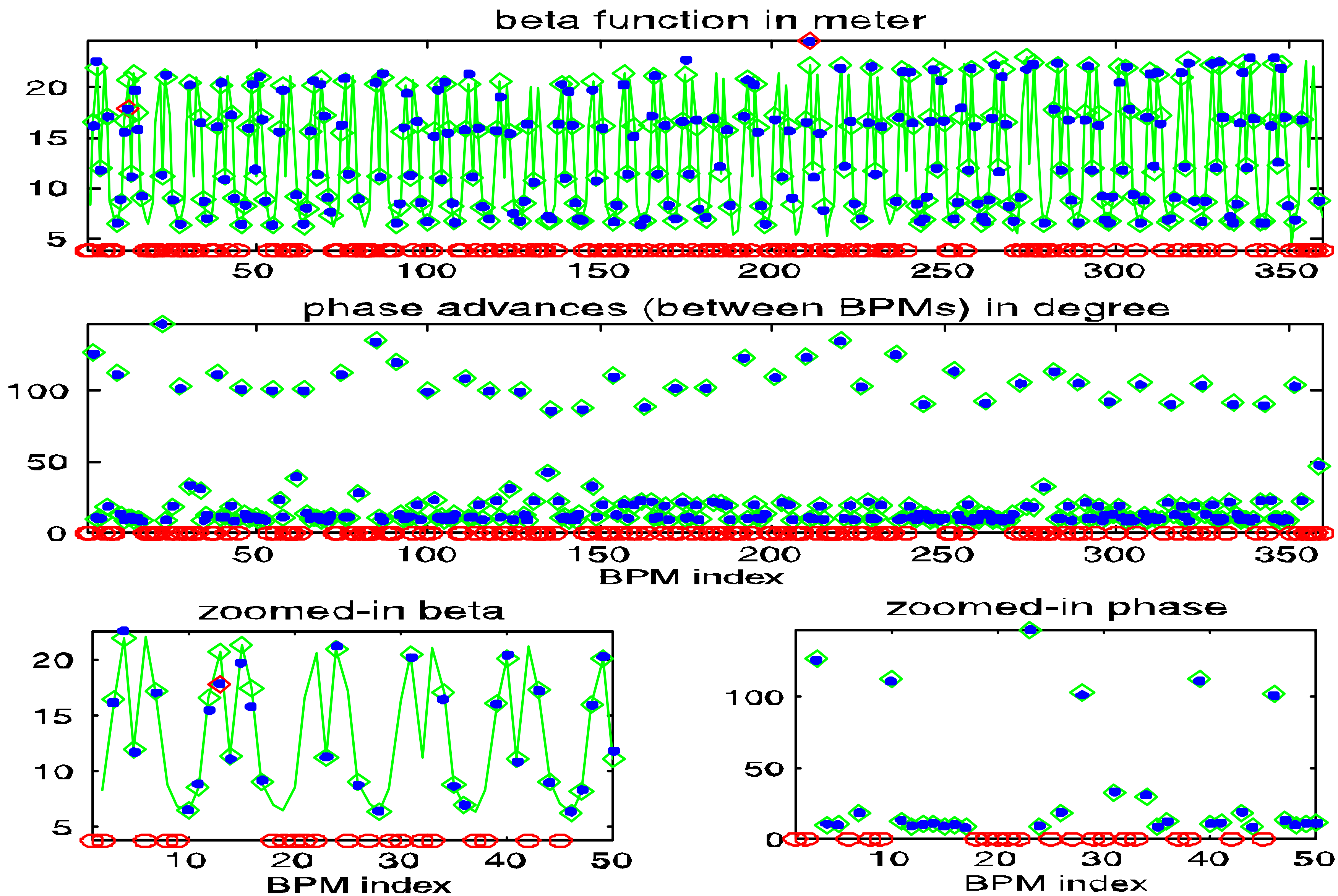
50
BPM index

C-X. Wang


beta function in meter
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phase advances (between BPMs) in degree
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BPM index
zoomed-in beta
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BPM index
zoomed-in phase
100
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0
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40
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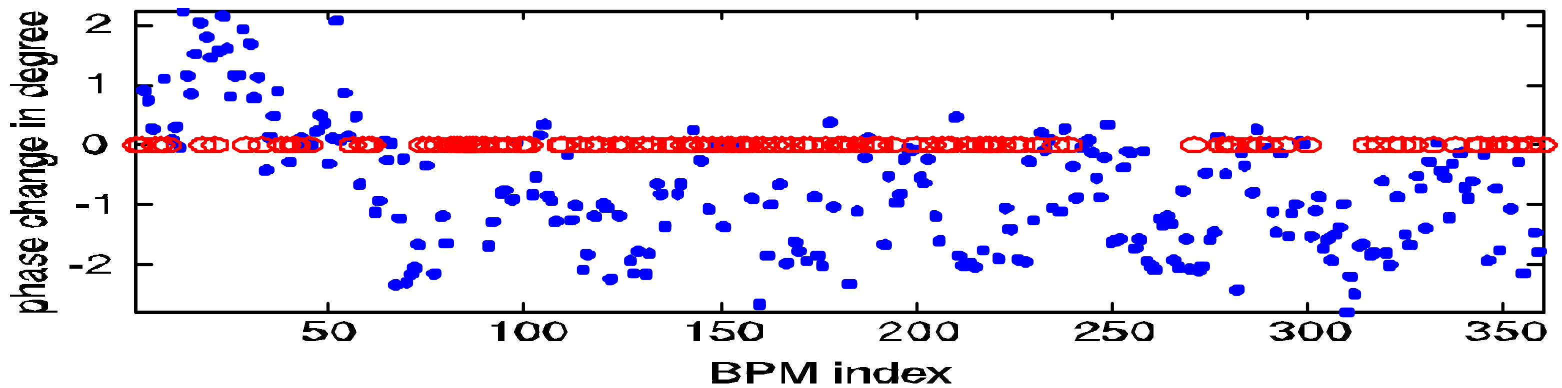
BPM index

C-X. Wang


phase change in degree
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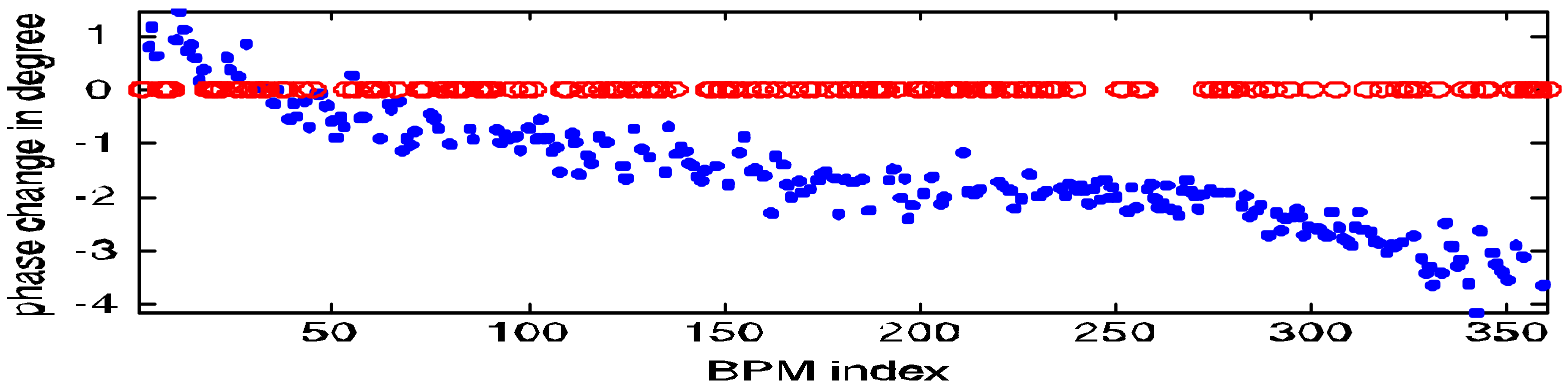
1
0
-1
-2
50
100
150
200
250
300
350
BPM index


phase change in degree
1
0
-1
-2
-3
-4
50
100
150
200
250
300
350
BPM index

C-X. Wang

Impedance and Collective Effects

- Impedance dominated by ID chambers, but other components also important (e.g., HOMs, scrapers)
- Tune slope increases with added ID chambers – TMCI threshold reduced
- Develop a complete, accurate impedance database
- Influence design of future components and chambers

- Horizontal instability observed above ~5 mA/bunch – this is the TMCI threshold
- Normal ops with high ξ allows a single-bunch limit up to ~10 mA but beam quality poor
- Motivation: understand physics and how to control instability; reproduce detailed dynamics above TMCI (also bunch lengthening and growth in energy spread with intensity)

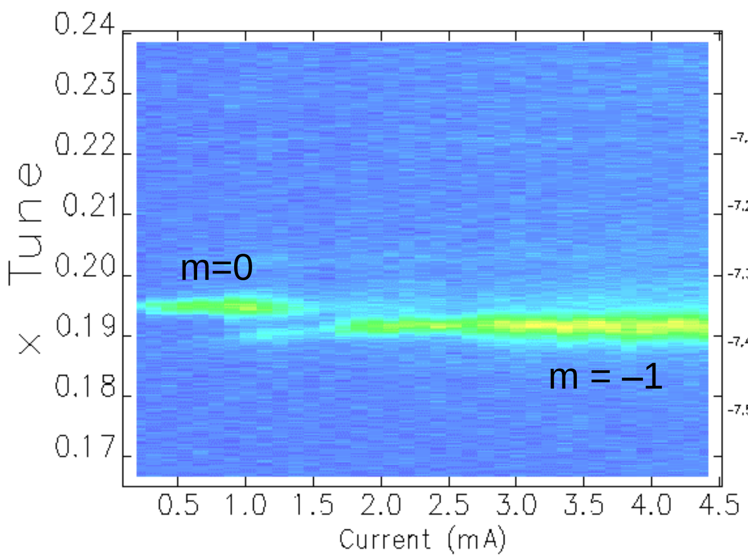
Single-bunch instability: transverse mode-coupling instability

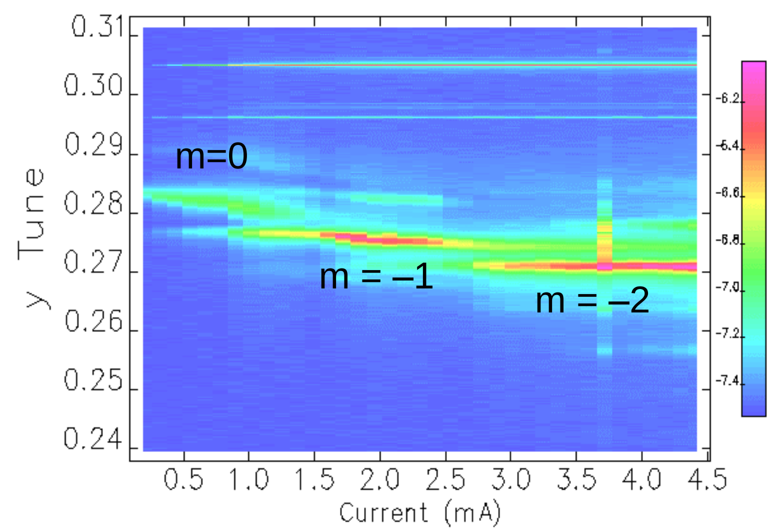
Force due to transverse wake defocuses beam, i.e., detunes betatron frequency.

When ν_β crosses ($m\nu_s$) modulation sidebands, synchrotron motion can couple to transverse plane and beam can be lost unless chromaticity is sufficiently large/positive.

Tune slope increases with no. of small gap chambers: mode merging threshold decreases.

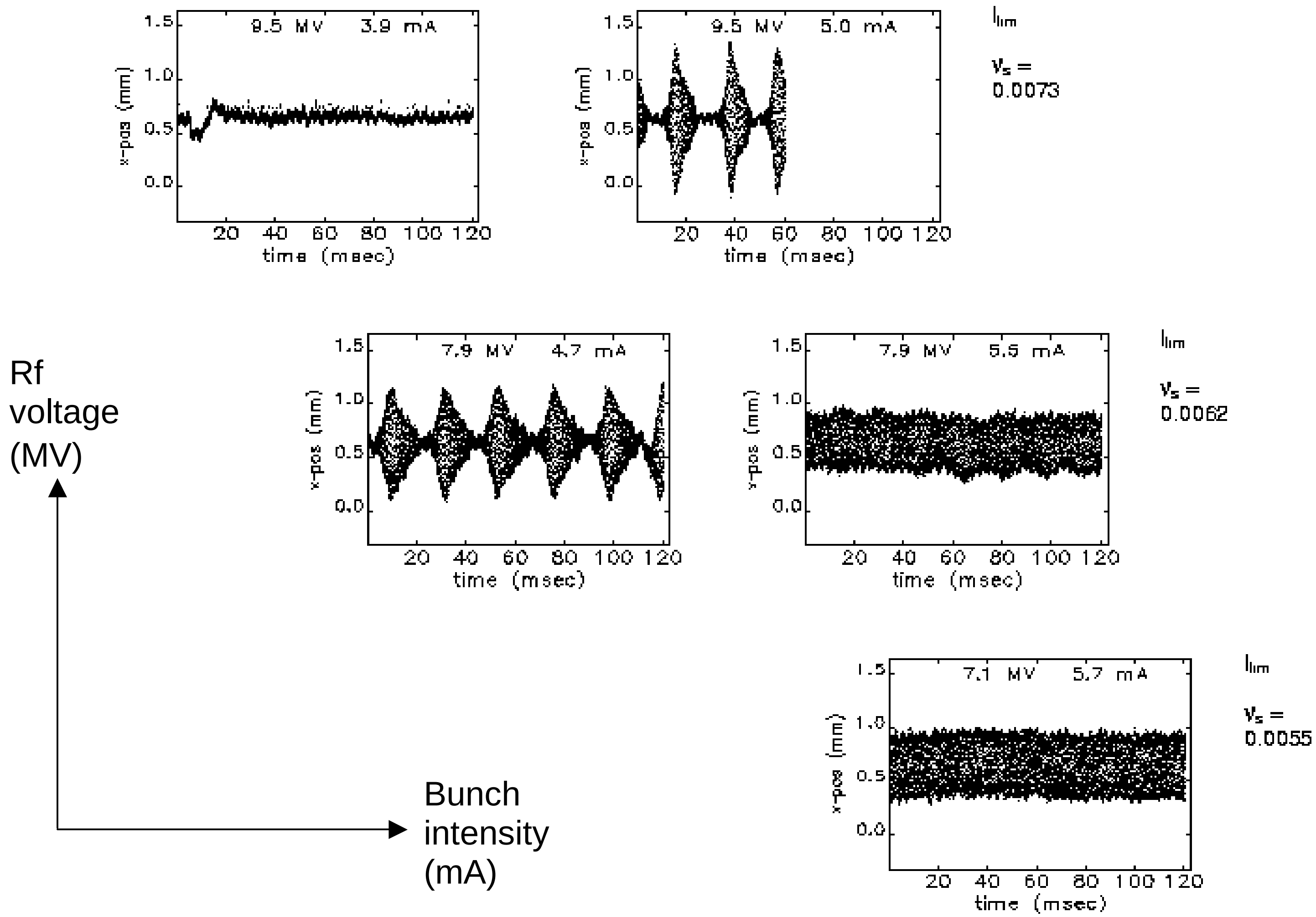
Horizontal $\xi_x > 1.3$, $\xi_y \approx 4$ **Vertical**





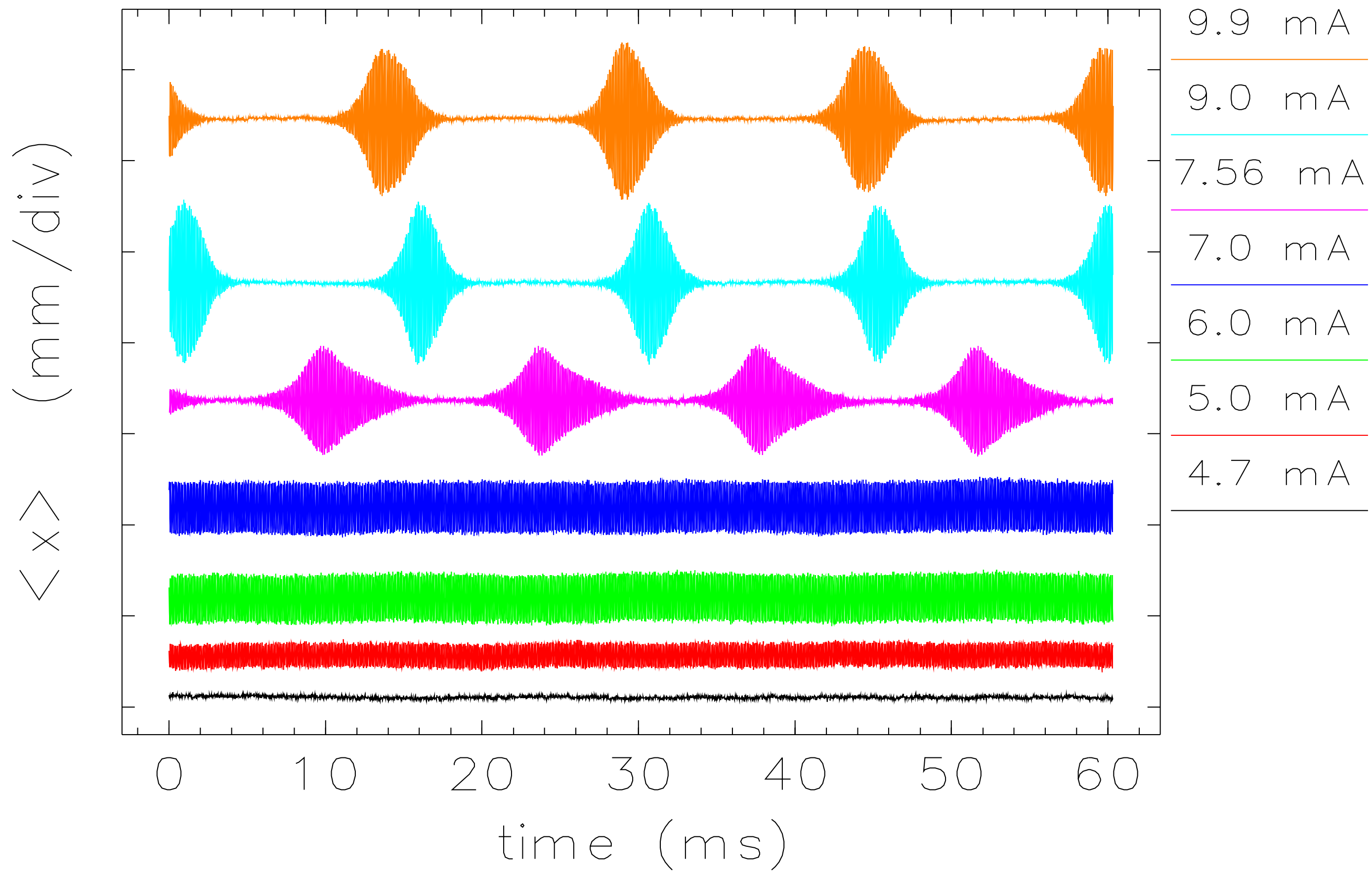
$\Delta\nu_x/\Delta I = -8\times10^{-4}$/mA $\Delta\nu_y/\Delta I = -2.6\times10^{-3}$/mA

(data courtesy of L. Emery [K. Harkay et al., Proc. of 1999 PAC, 1644])



Early data using beam position monitor turn-by-turn histories showed horizontal centroid oscillations whose bunch intensity instability onset and mode (bursting vs. steady-state amplitude) varied with rf voltage (chromaticities: $\xi_x = 1.3$, $\xi_y = 3.9$) (2/15/1999)

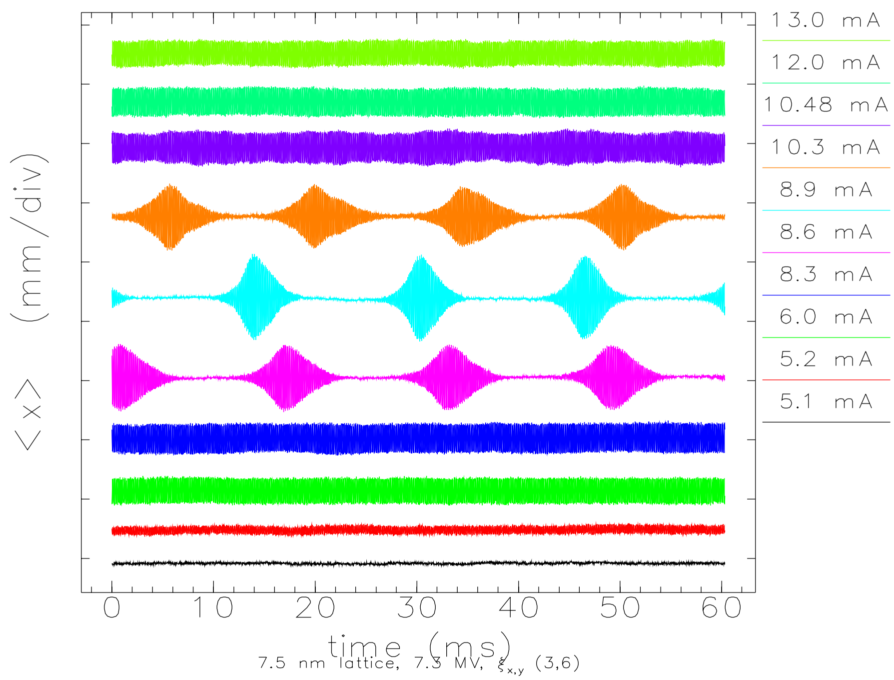
Large <x> oscillations above mode-merging threshold (V_{rf} 9.4 MV case shown): some Users will observe an effective emittance blowup, $\Delta\varepsilon_x$



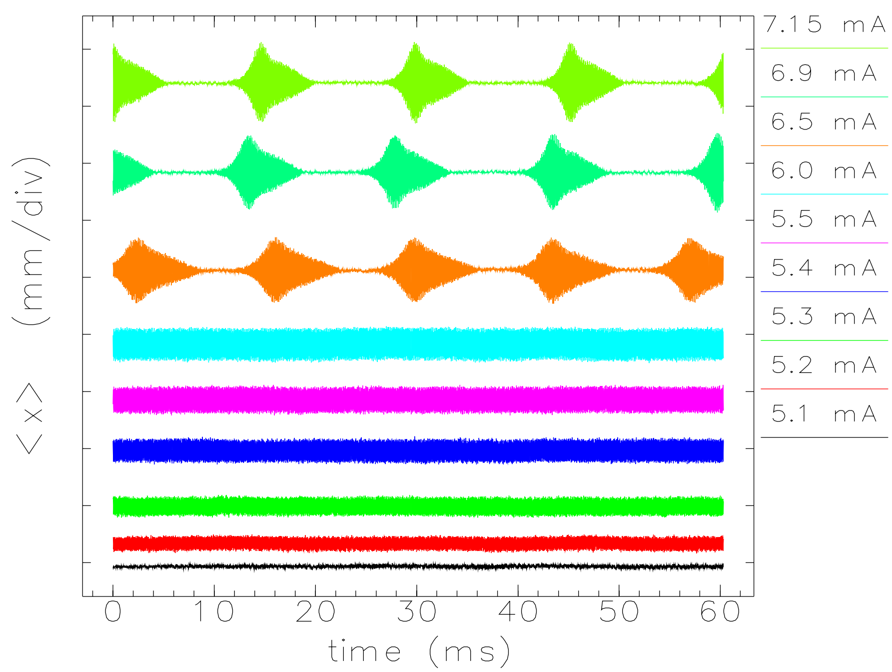
Note: bunch length σ_z, energy spread δ, and emittance ε_x also vary with current (ε_x decoherence NOT 100% of <x> oscillation amplitude; σ_x = 220 μm (7.5 nm-r lattice))

Variations with different machine parameters

7.5-nm lattice, Vrf = 7.3 MV, $\xi_{x,y}$ = (3,6)

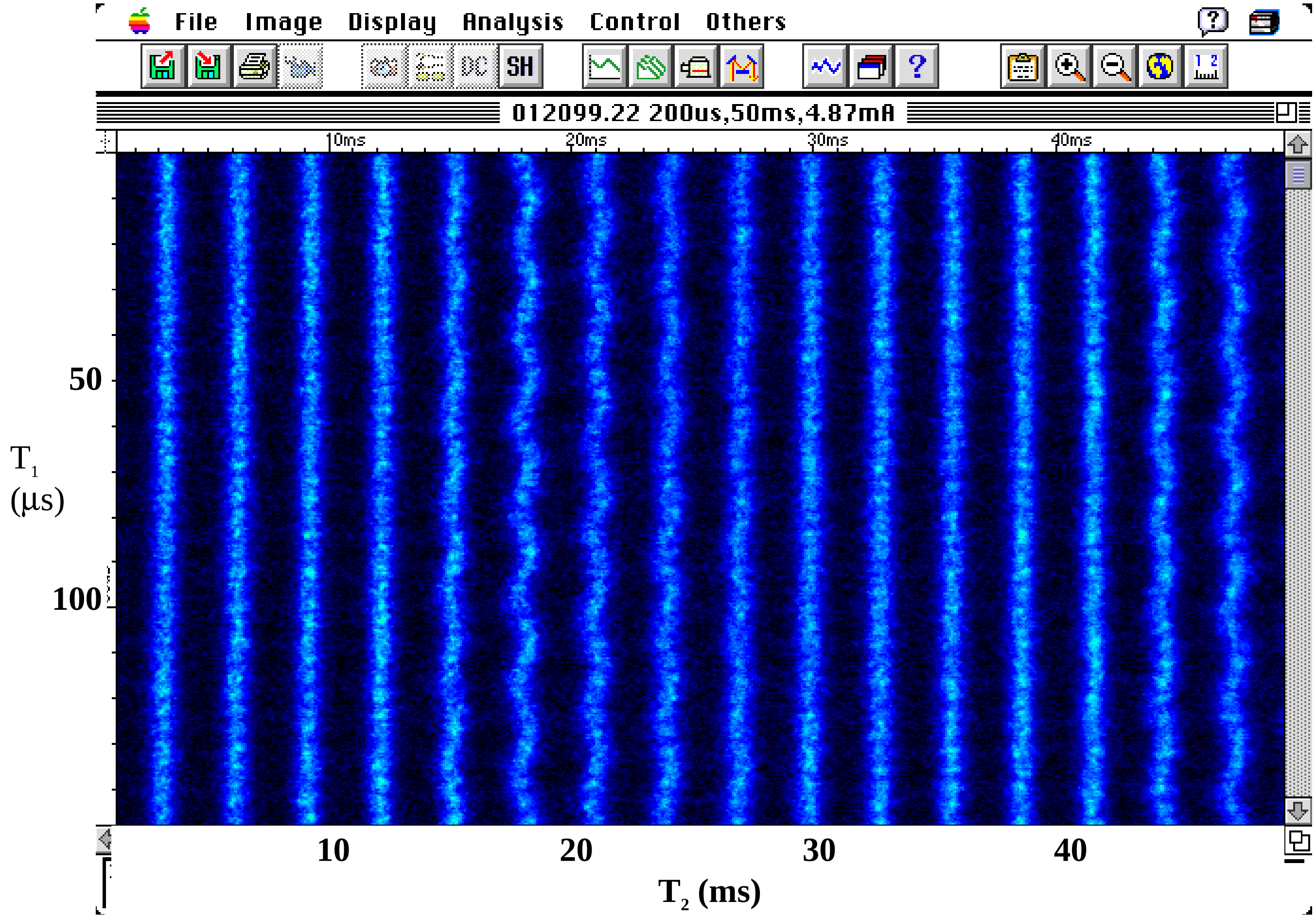


3.9-nm lattice, Vrf = 9.5 MV, $\xi_{x,y}$ = (3.2,5.8)

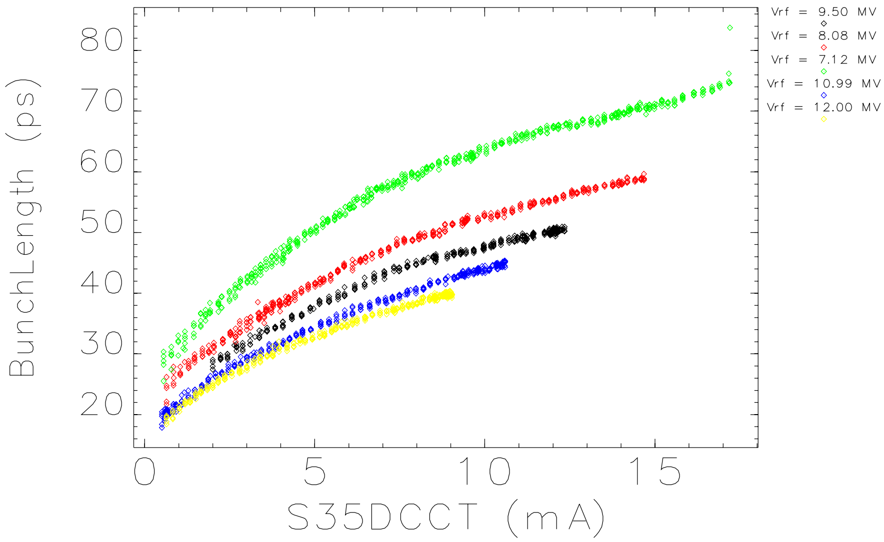


Dual-sweep streak camera horizontal image of single bunch undergoing coherent horizontal oscillations in bursting mode: bunch does not completely decohere

[data courtesy of B. Yang; K. Harkay et al., Proc of 1999 PAC, 1644]



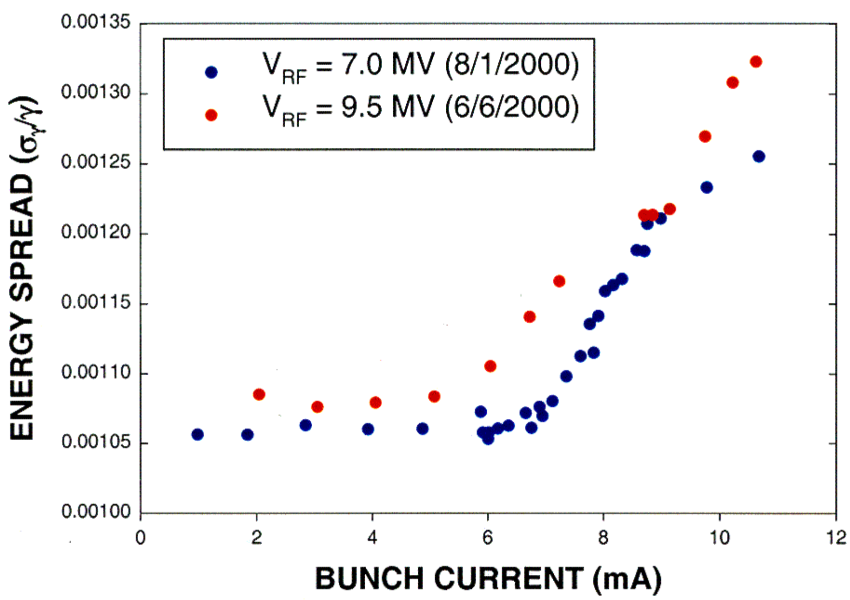
Measured bunch lengthening vs V_{rf}
(L. Emery, M. Borland, A. Lumpkin)



no 5-mm chambers (March 2000)

$Z_{||}/n \approx 0.5\ \Omega$ [estimated, Y.-C. Chae et al., Proc. of 2001 PAC, 1817]

ENERGY SPREAD AS A FUNCTION BUNCH CURRENT



high ξ_x (B. Yang, L. Emery, Y.-C. Chae, K. Harkay)

Impedance Database

- Goal

Wakepotential(APS Storage Ring) =

20*(8-mm ID Chamber) + 2*(5-mm ID Chamber) +

400*(BPM) + 80*(C2 Crotch Absorber) +
……..

- Standardize Wakepotential

1. Data in SDDS format
   - S, Wx, Wy, Wz

2. Uniform simulation conditions
   rms bunch length ➔ SIGz = 5 mm,
   mesh size ➔ dz = 0.5 mm,
   wakelength ➔ SBT = 0.3 m

3. Deposit the authorized wakepotentials in
   ~aps/ImpedanceDatabase/SR
   ➔ Available to everyone to read files

Y.-C. Chae

Vacuum Chamber Components

- Old components (experience)

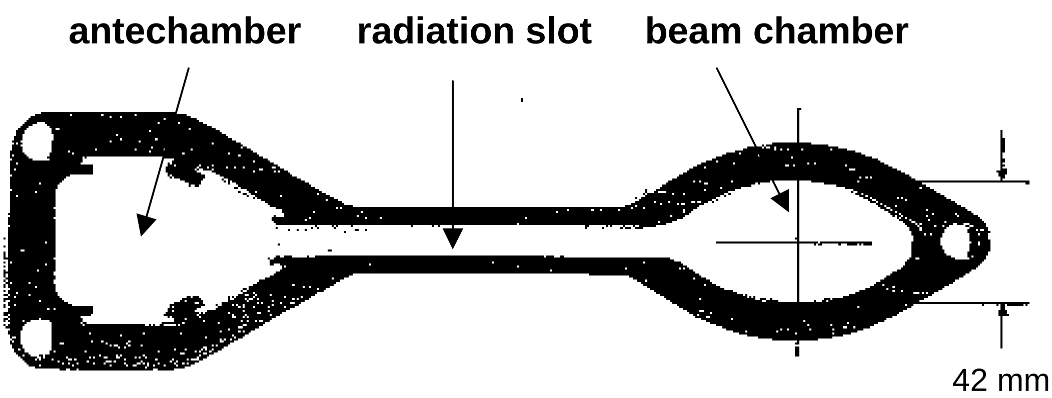
  - Insertion Device Chambers
  - RF Cavities + Transition
  - Crotch Absorbers
  - Horizontal/Vertical Scrapers
  - Septum Intrusion
  - Stripline Monitors …….

- New components

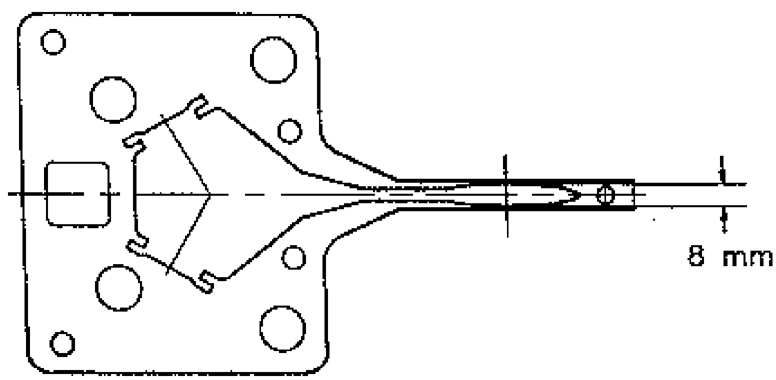
  - BPMs
  - SR absorber between rf cavities
  - Vacuum port (slotted rf screen)
  - Shielded bellow

APS Storage Ring chambers

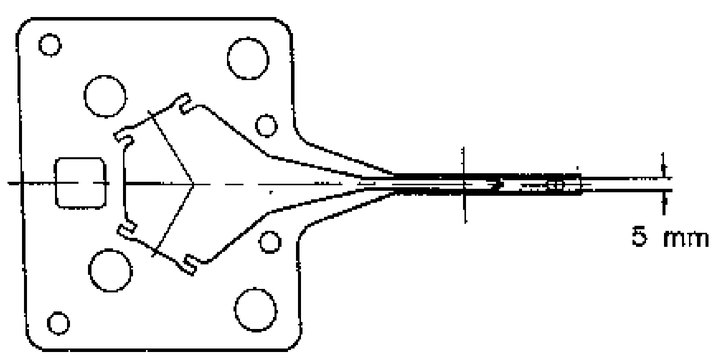
Standard



8-mm gap ID chamber

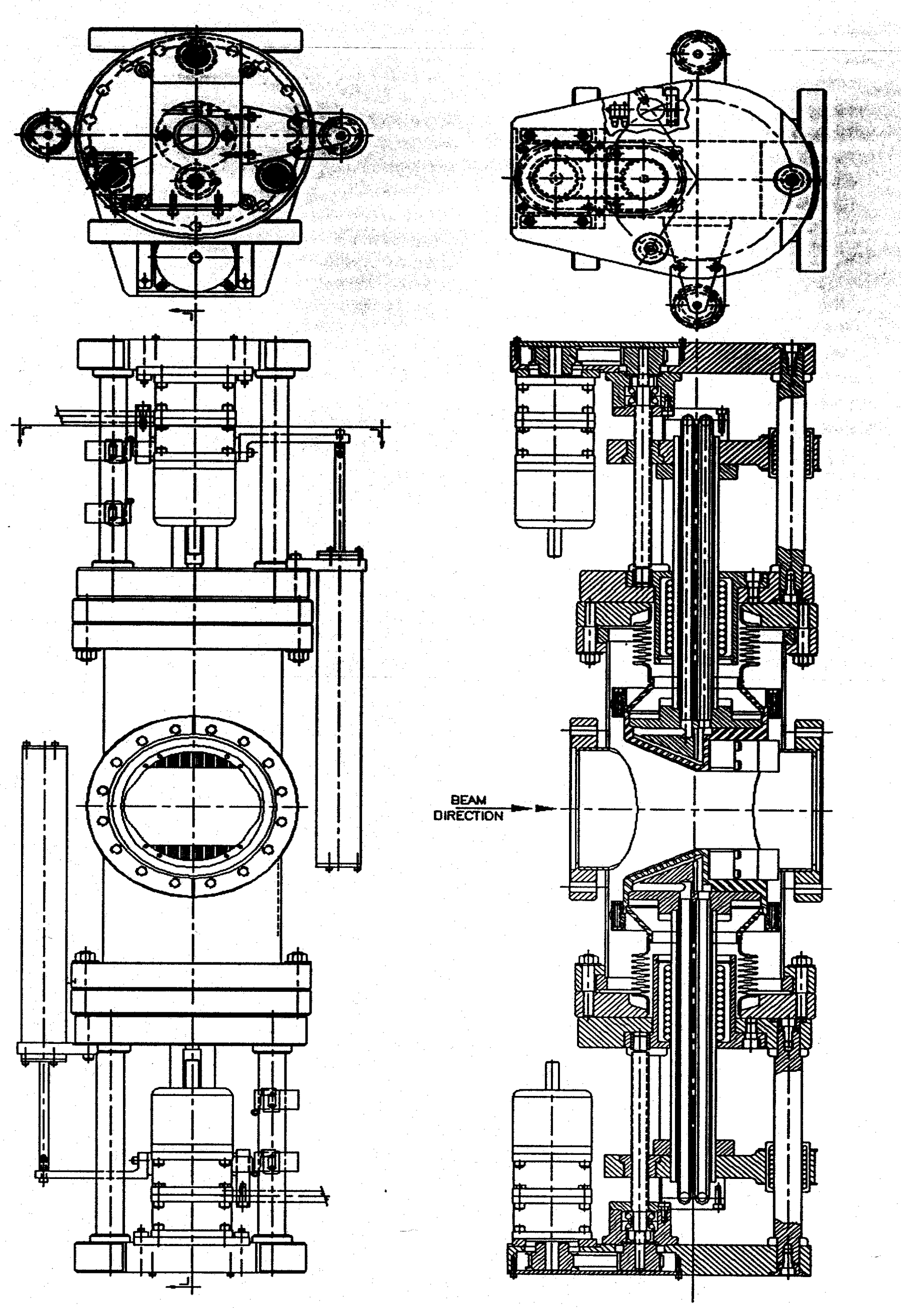


5-mm gap ID chamber



Impedance Database (cont.)

SR. VERTICAL SCRAPER



Example: Insertion Device Chambers

- **Insertion Device Chambers**

  - 5-mm-gap chamber
  - 8-mm-gap chamber
  - 12-mm-gap chamber

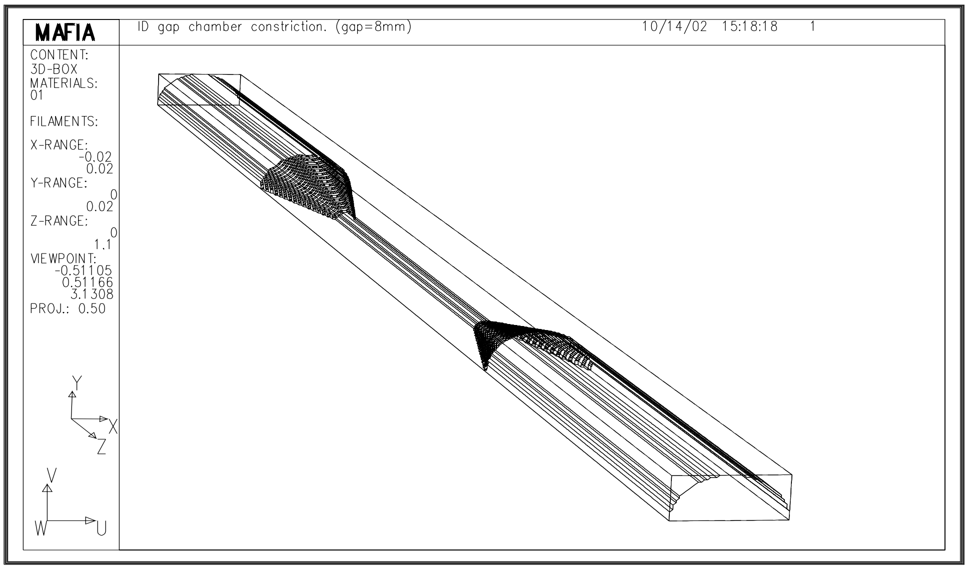
- **Steps taken for 3-D Wakepotential**

I. 2-D ABCI calculation for circular chamber (High confidence)
II. 2-D ABCI vs. 3-D MAFIA for circular pipe (Compare)
III. 3-D MAFIA for elliptical chamber (Final result)

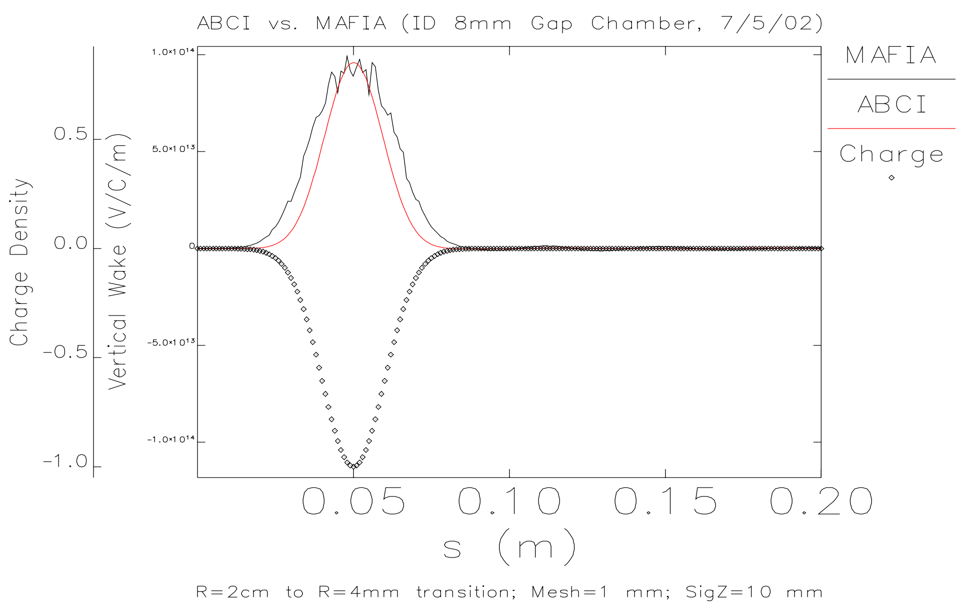
Impedance Database (cont.)

2-D ABCI vs. 3-D MAFIA (Compare)

Geometry



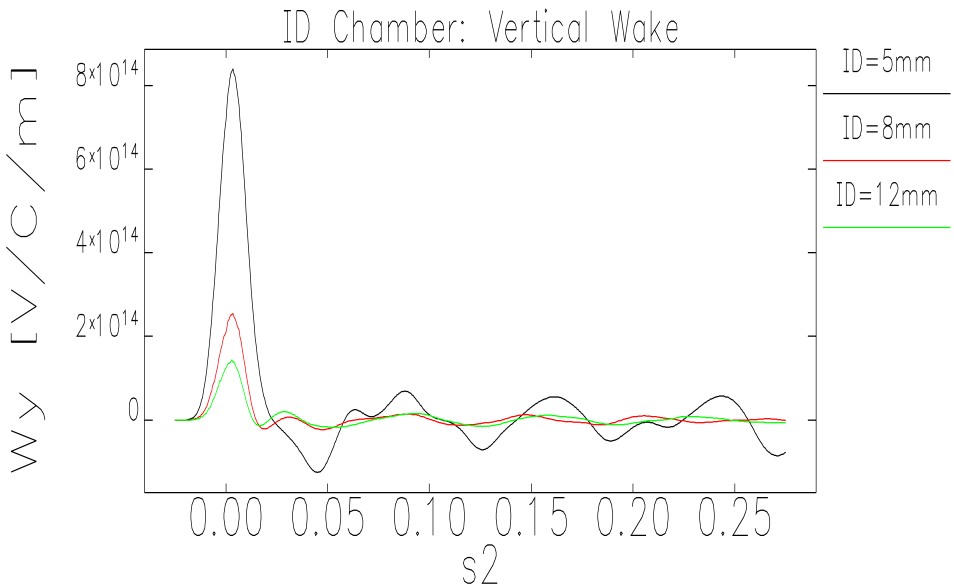
Results

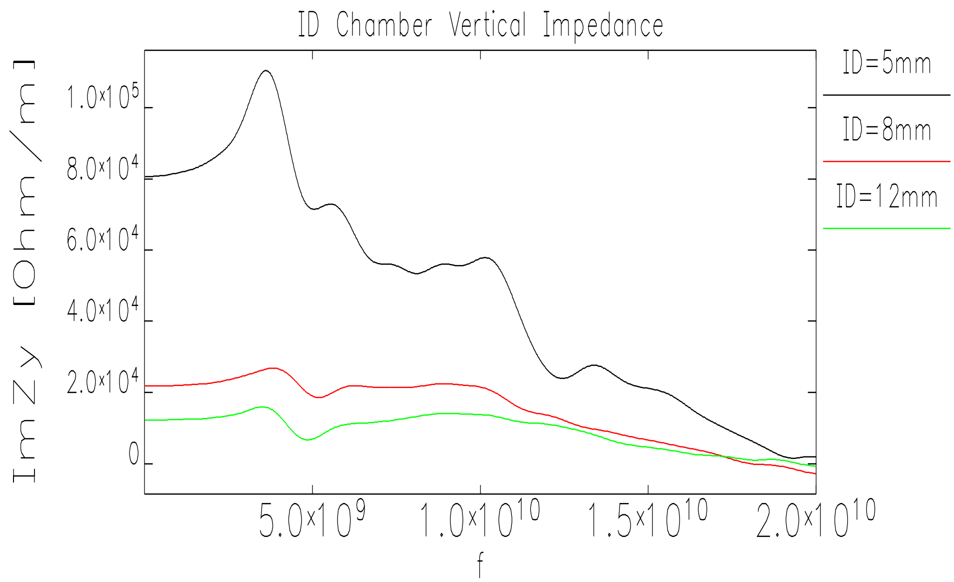


Y.-C. Chae

Impedance Database (cont.)

3-D MAFIA Results for Elliptical ID Chamber (Wakepotential & Impedance)

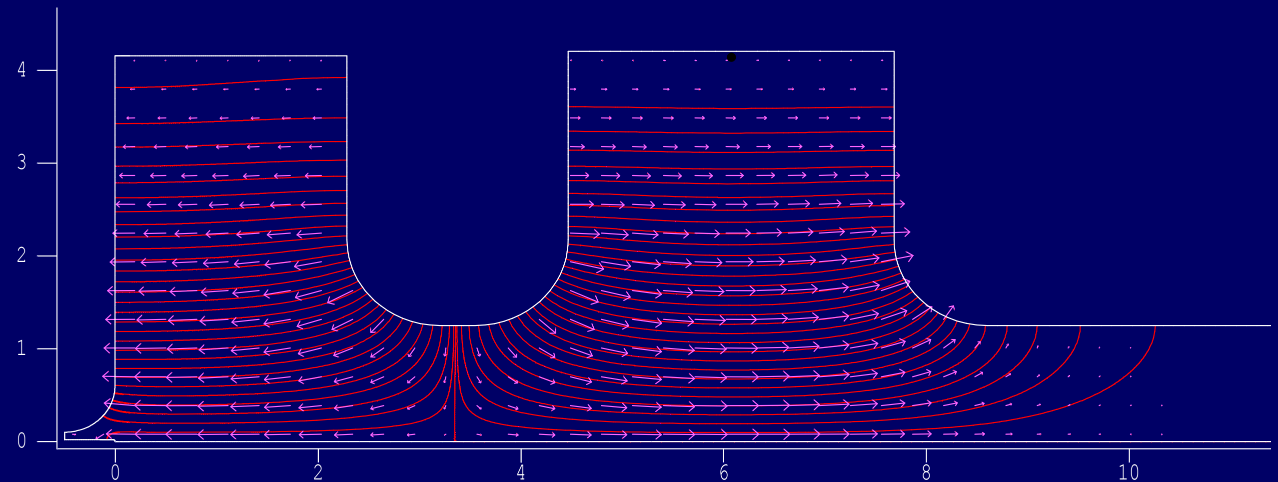


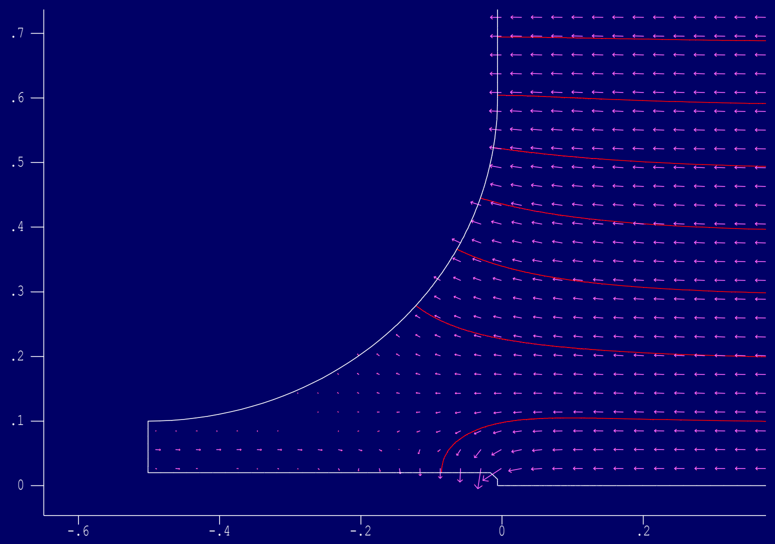


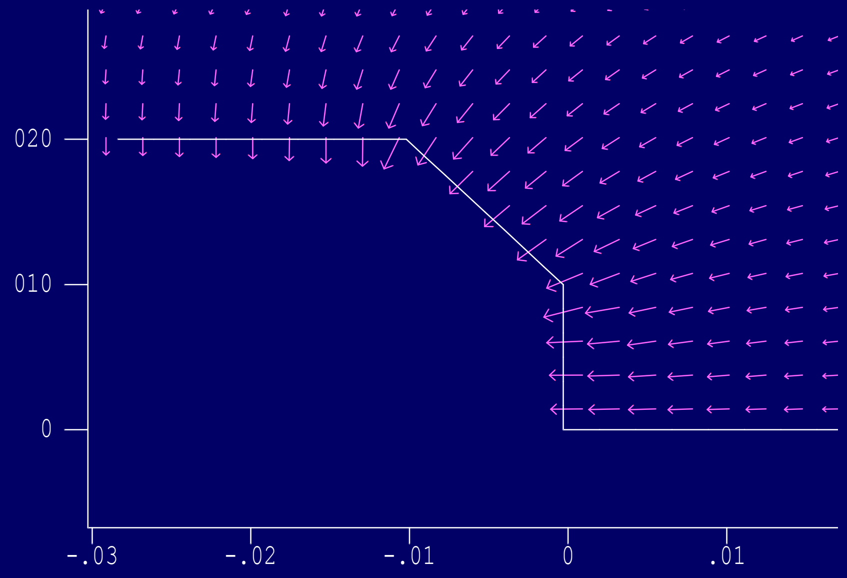
Y.-C. Chae

J.W. Lewellen

π-Mode Gun with Needle Cathode



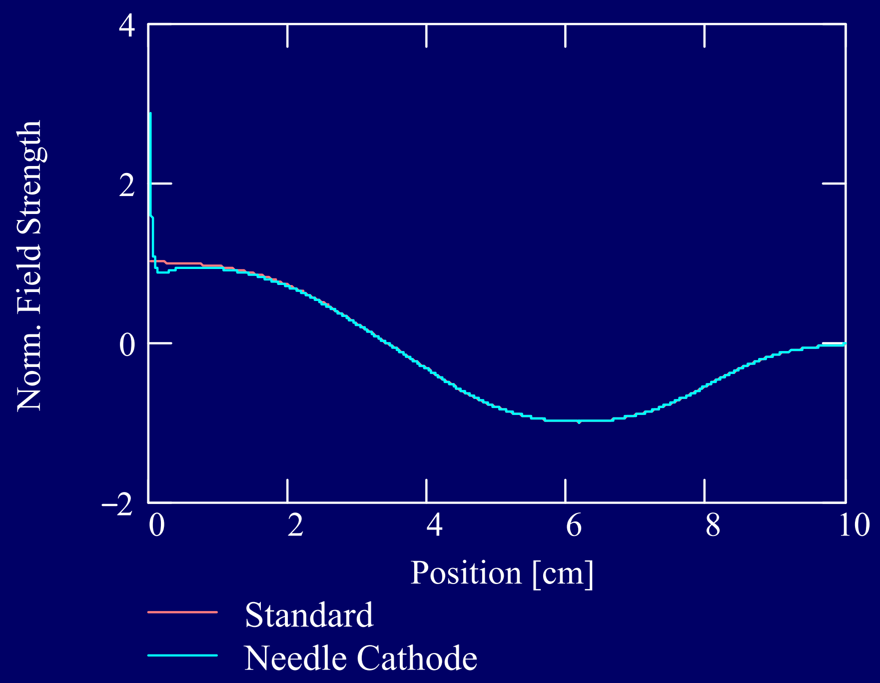


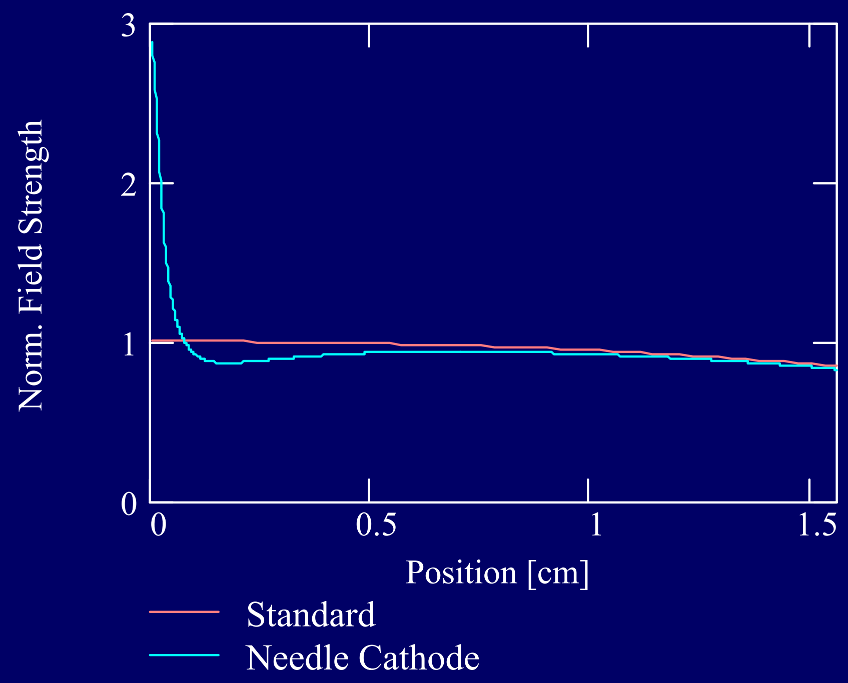


J.W. Lewellen

On-Axis Field Comparison

200-µm flat top radius, 300-µm needle radius

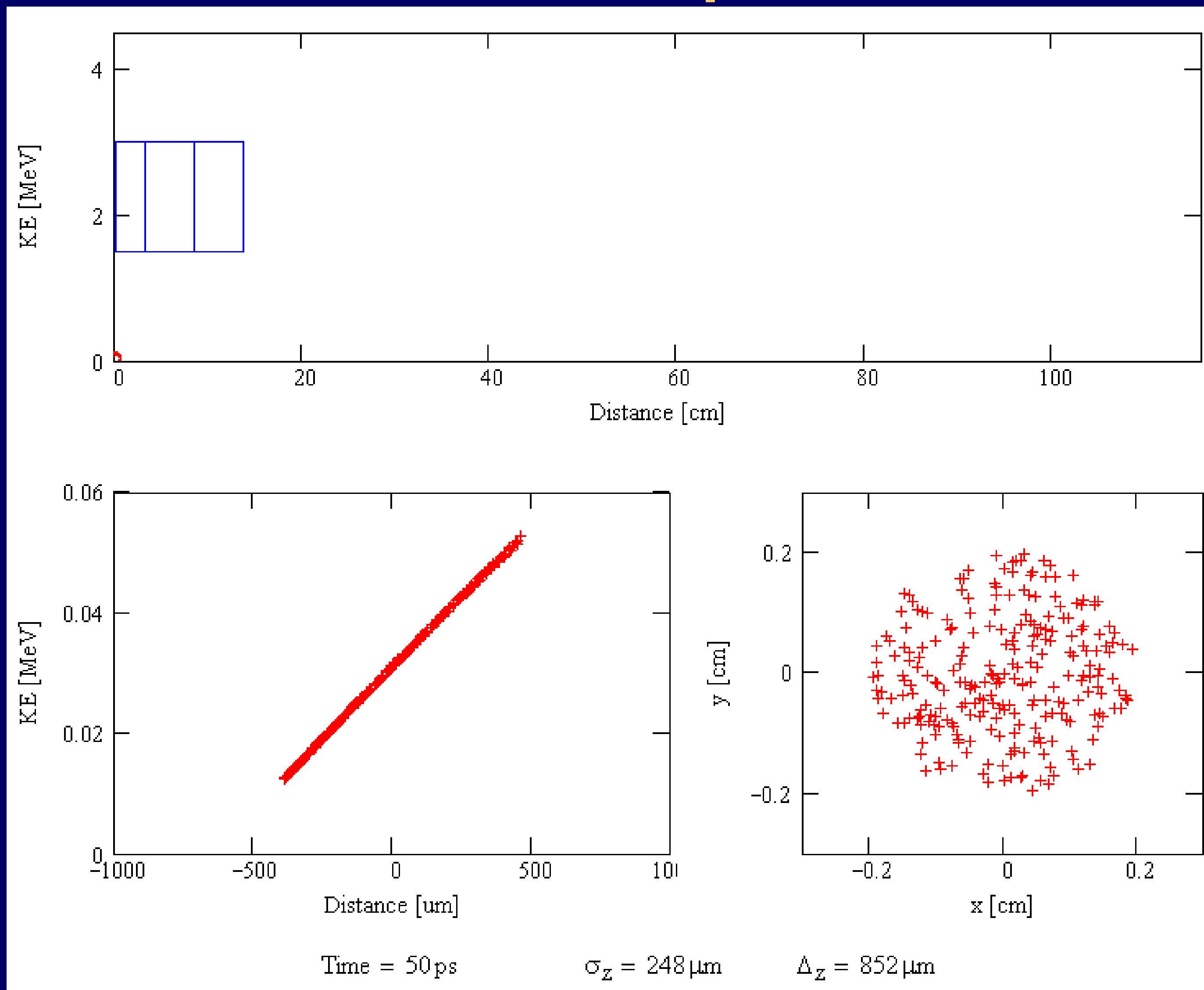




"Effective" needle height is ~ 1.3 mm

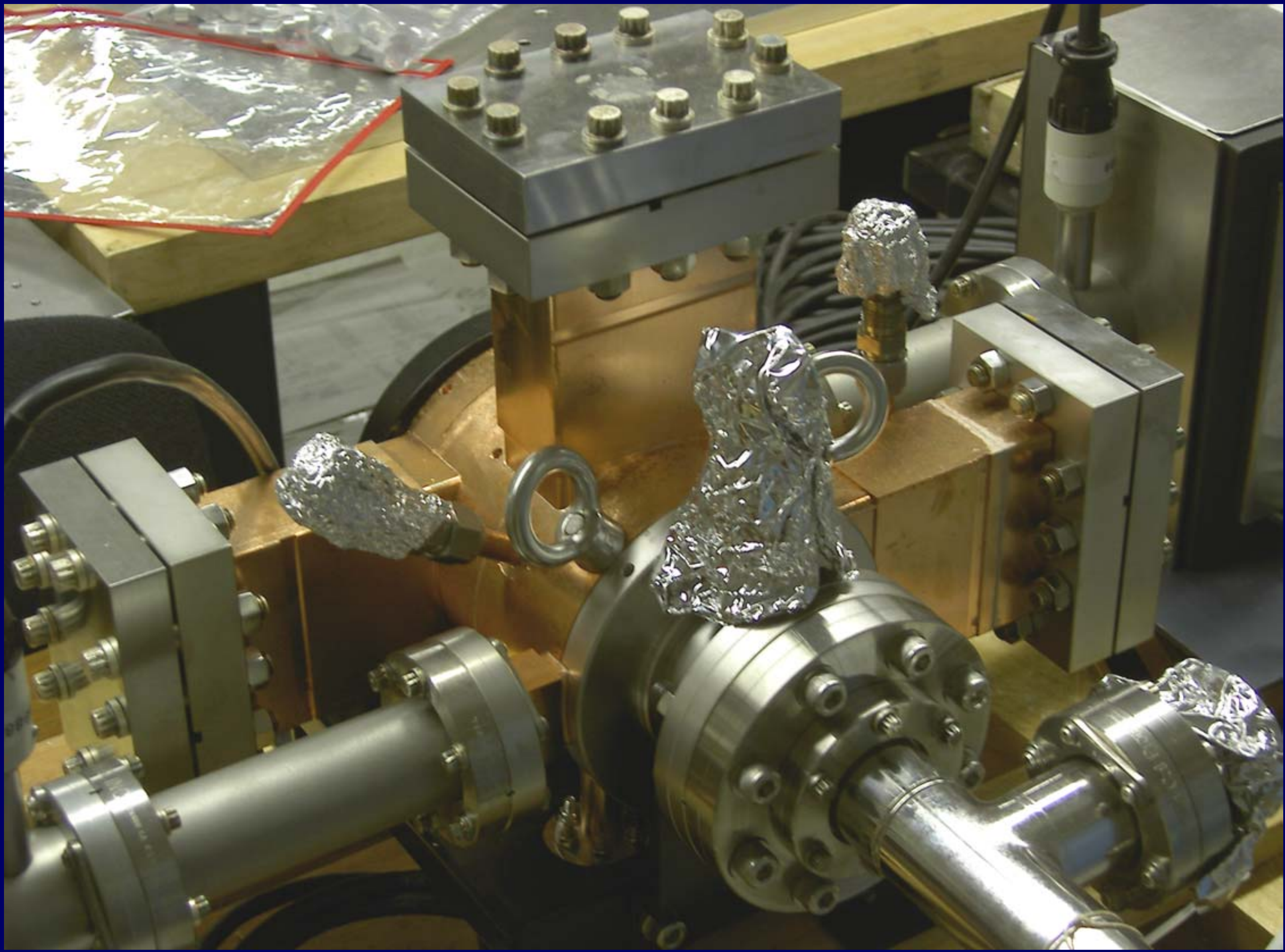
J.W. Lewellen

Ballistic Compression



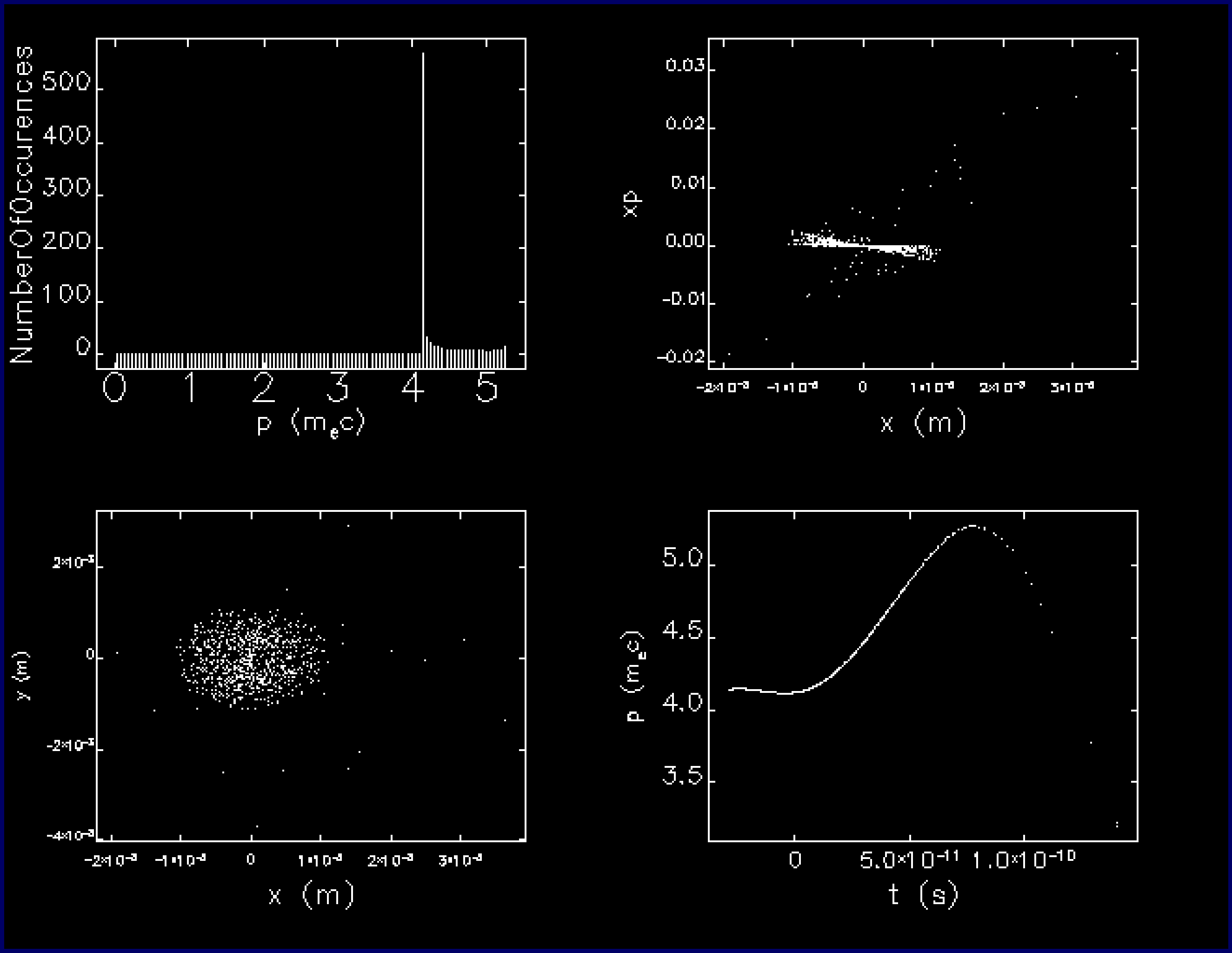
J.W. Lewellen

The BBC Gun



J.W. Lewellen

Stupid Gun Tricks – Energy Compression



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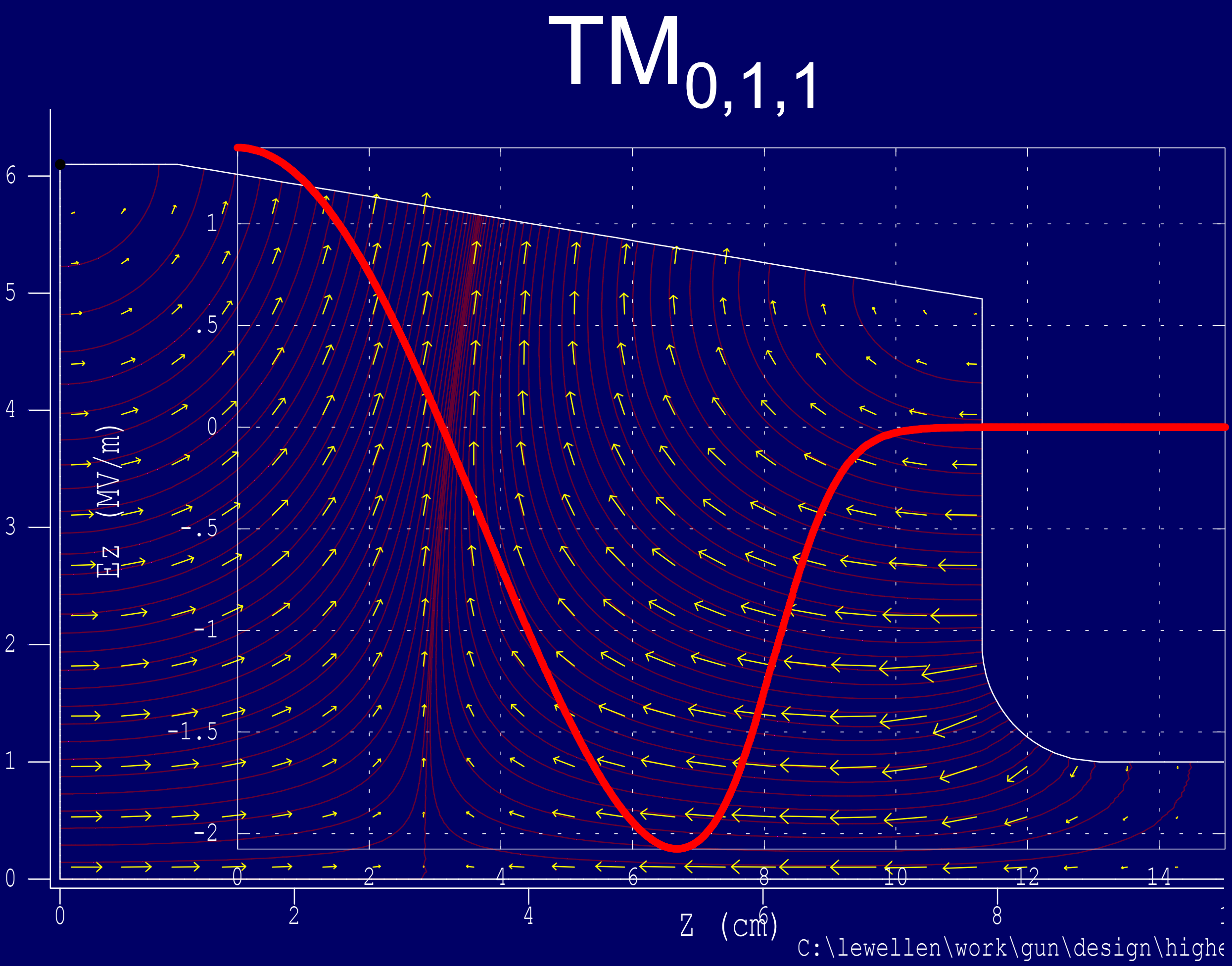
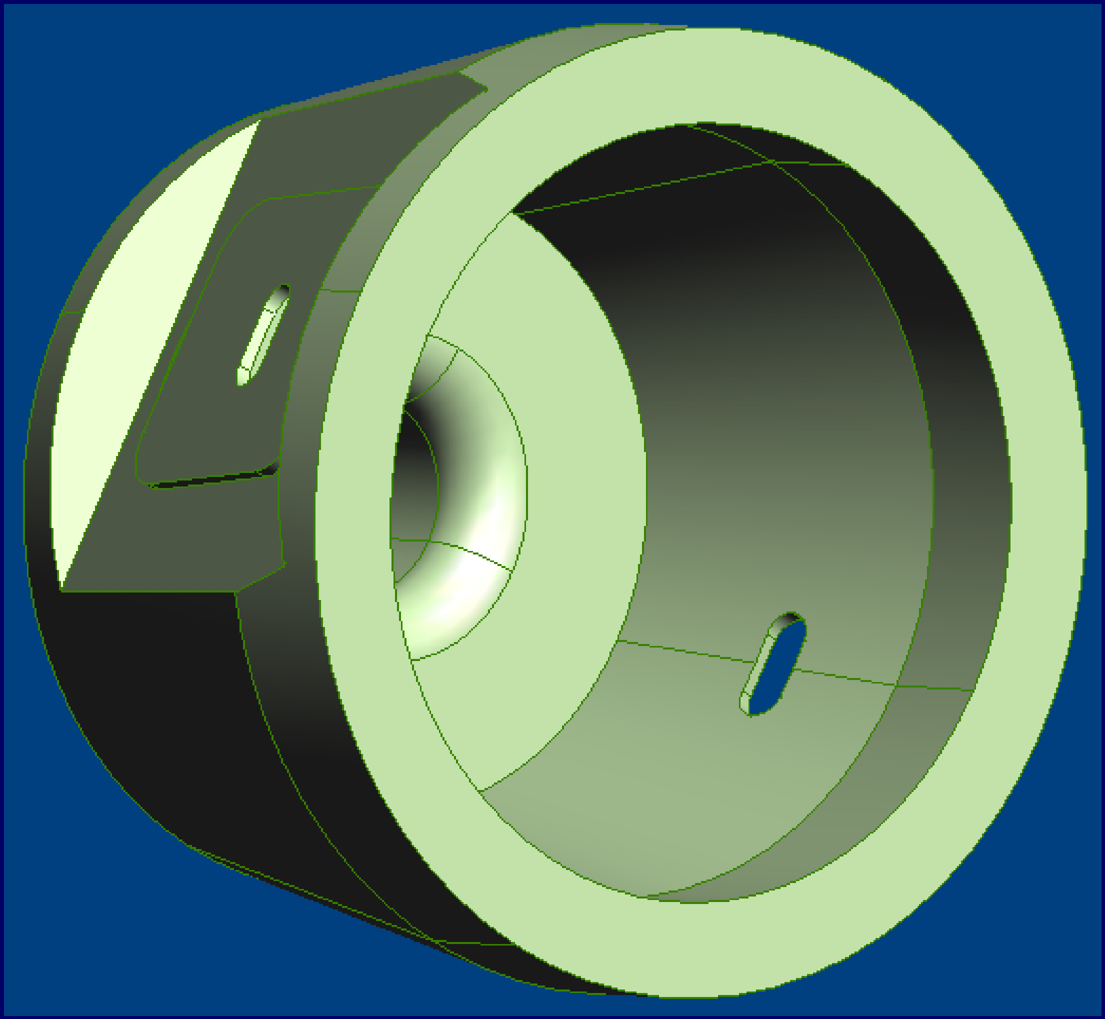
$TM_{0,1,1}$ Photoinjector Design



J.W. Lewellen

Higher-Order-Mode Gun High-Power Prototype Design



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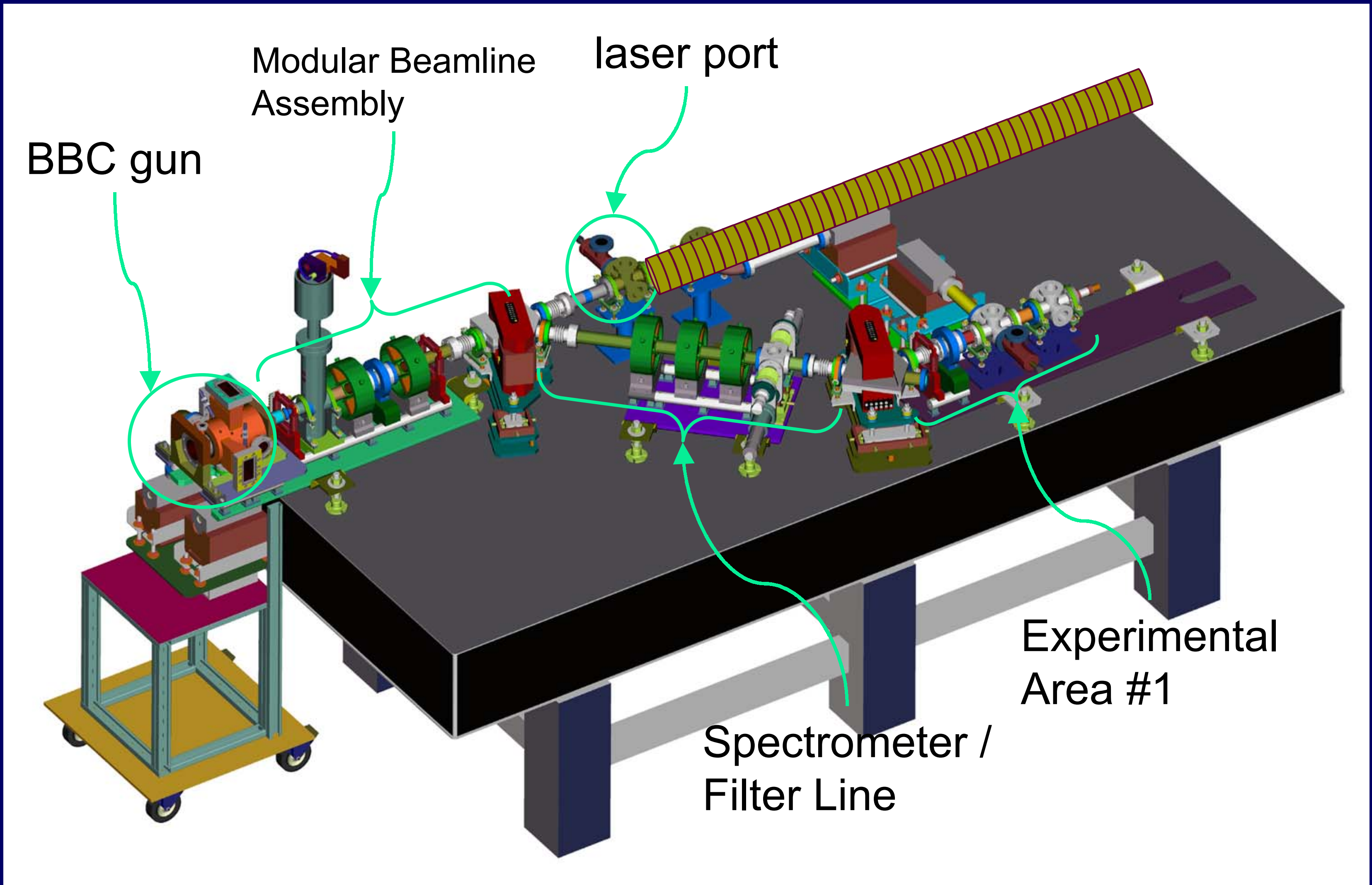
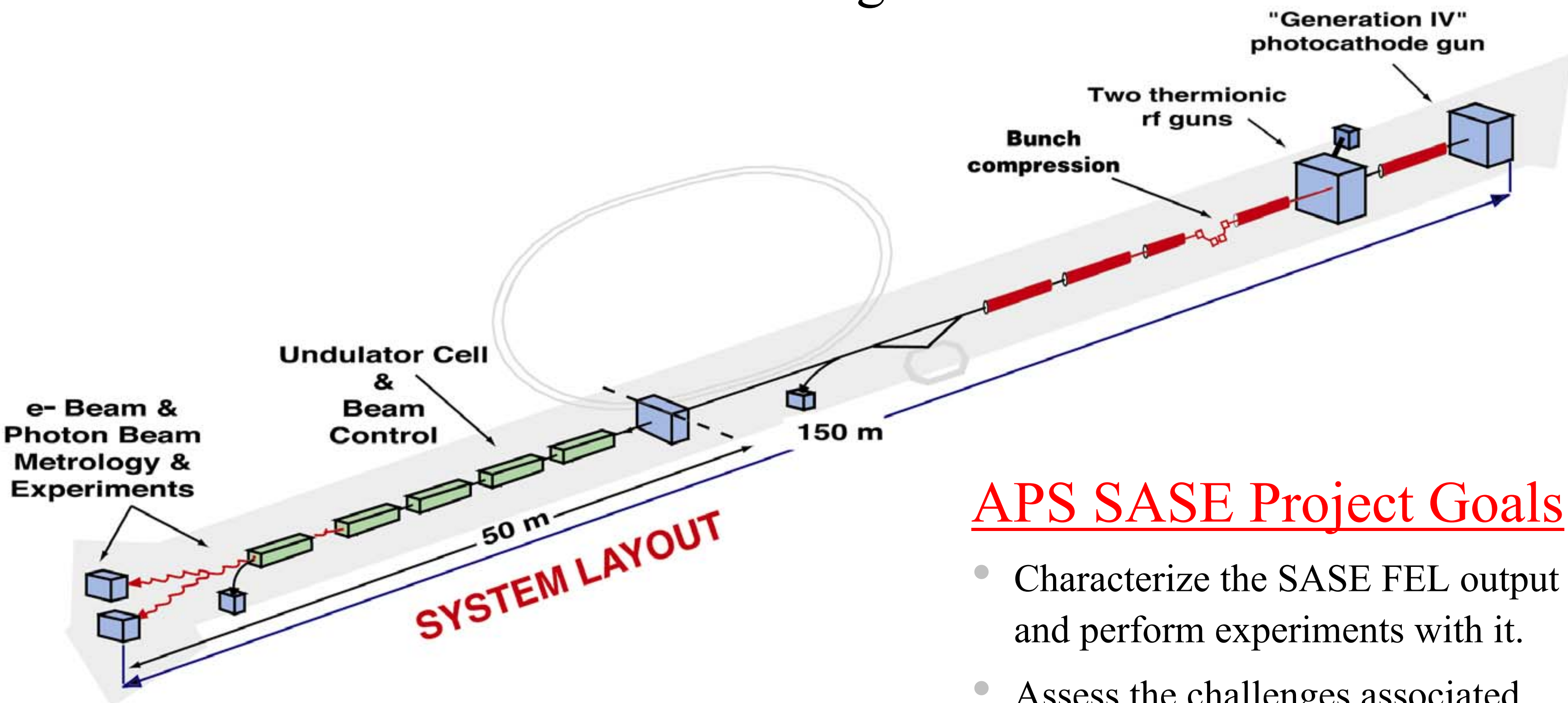
Status and Future Plans



The APS SASE FEL Schematic

The Low-Energy Undulator Test Line System
Present Configuration

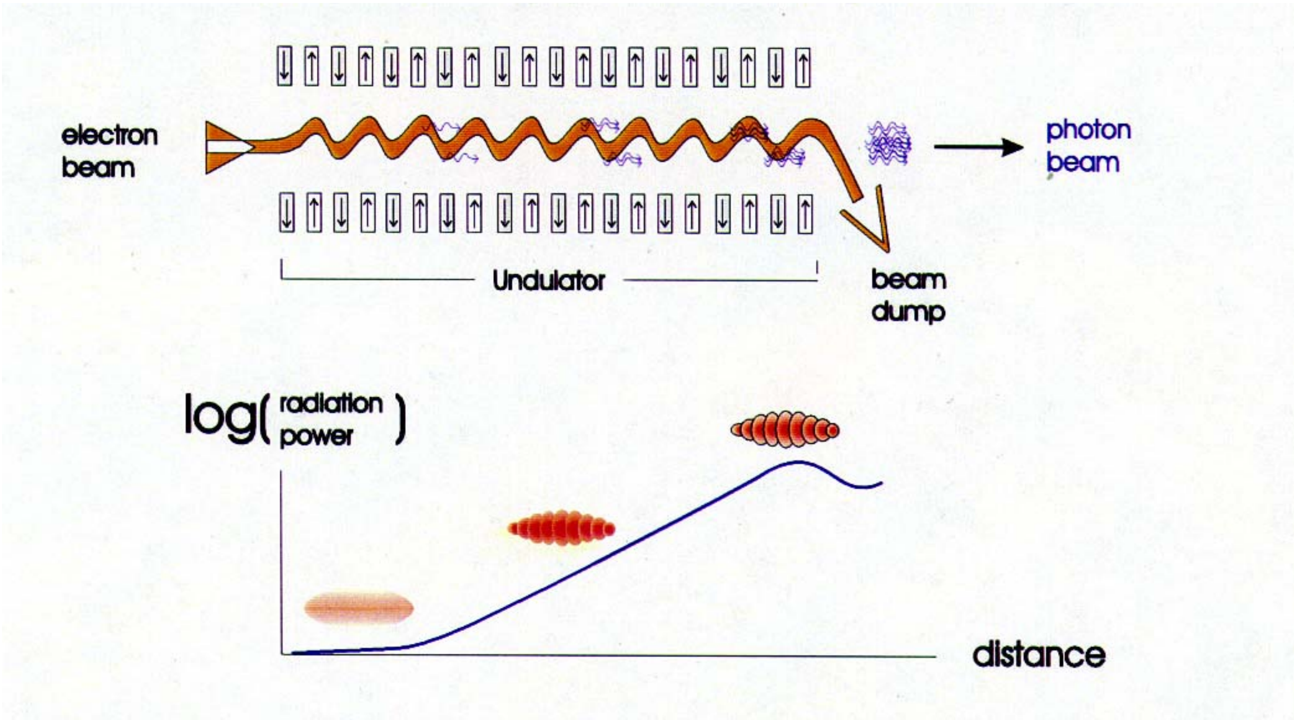


APS SASE Project Goals

- Characterize the SASE FEL output and perform experiments with it.
- Assess the challenges associated with producing a SASE FEL in preparation for an x-ray regime machine.

S. Milton

Self-Amplified Spontaneous Emission



Electrons are bunched under the influence of the light that they radiate.
The bunch dimensions are characteristic of the wavelength of the light.

Excerpted from the TESLA Technical Design Report, released March 2001

S. Milton

Basic Parameters for the APS FEL

PARAMETERS			
Wavelength [nm]	Regime 1 530	Regime 2 120	Regime 3 51
Electron Energy [MeV]	217	457	700
Normalized rms Emittance (π mm-mrad)	5	3	3
Energy Spread [%]	0.1	0.1	0.1
Peak Current [A]	100	300	500
Undulator Period [mm]	33		
Magnetic Field [T]	1.0		
Undulator Gap [mm]	9.3		
Cell Length [m]	2.73		
Gain Length [m]	0.81	0.72	1.2
Undulator Length [m]	5 x 2.4 then 9 x 2.4	9 x 2.4	10 x 2.4

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Undulator Line Details

Length	9 x 2.4 m
Period	3.3 cm
Gap	9.4 mm
Field	1 T
K	3.1
Intermodule gap	~ 38 cm

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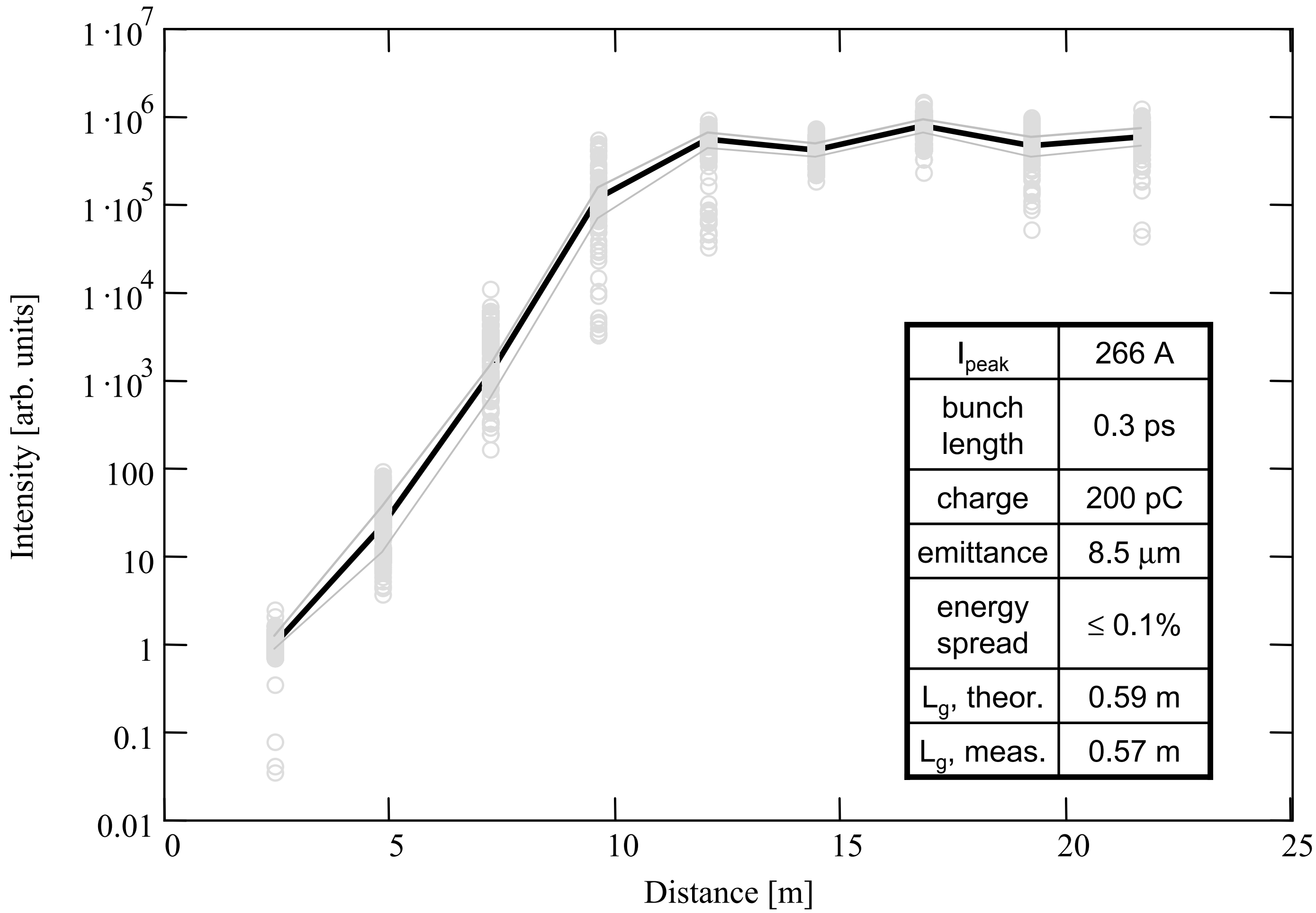
Optical Intensity Gain



I_{peak}	266 A
bunch length	0.3 ps
charge	200 pC
emittance	8.5 µm
energy spread	≤ 0.1%
L_g, theor.	0.59 m
L_g, meas.	0.57 m

530nm
10 March 01
dataset DS1

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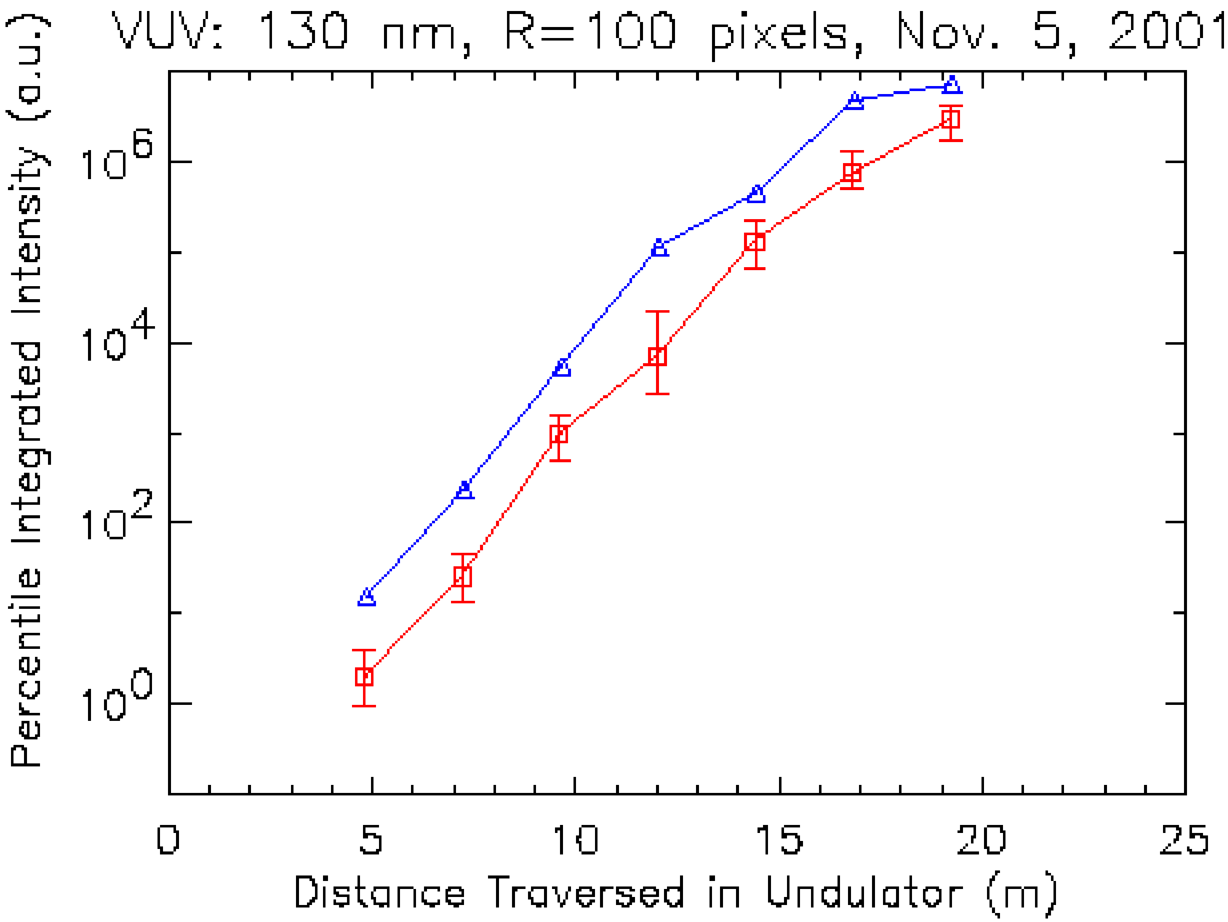
Recent Results at 130 nm



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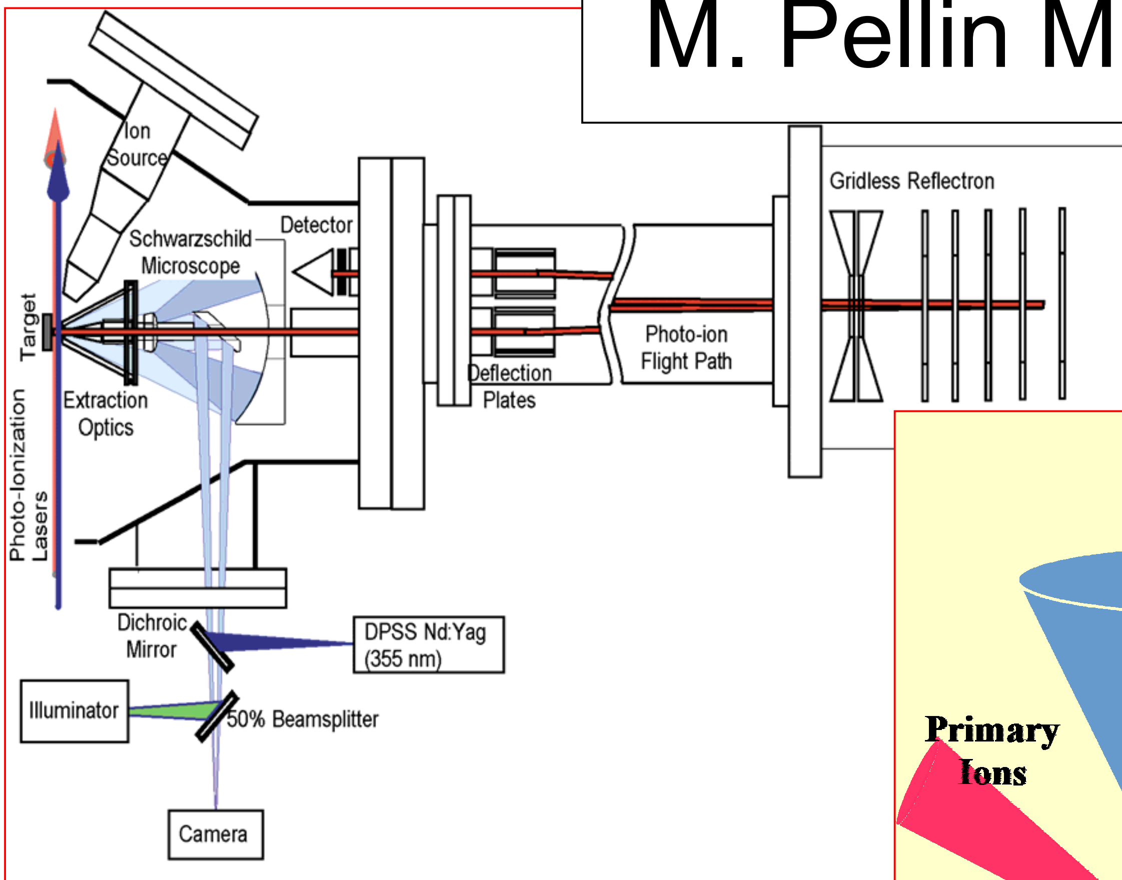
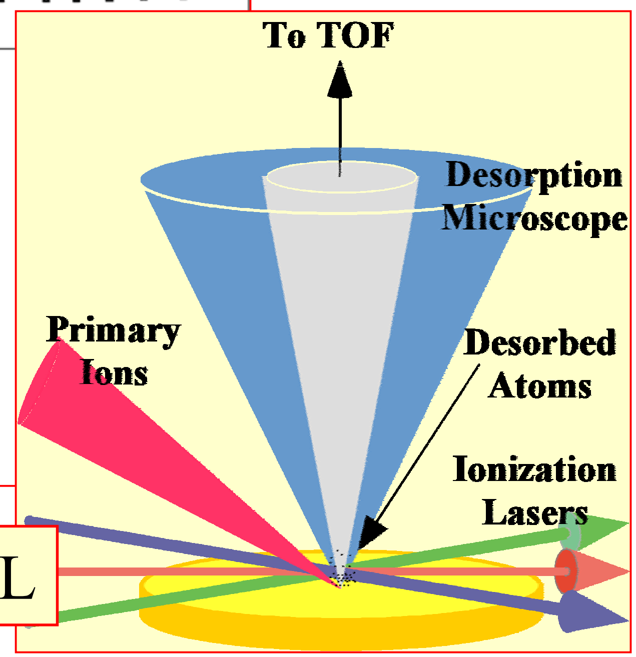
The First APS FEL Experiment

M. Pellin MSD/ANL

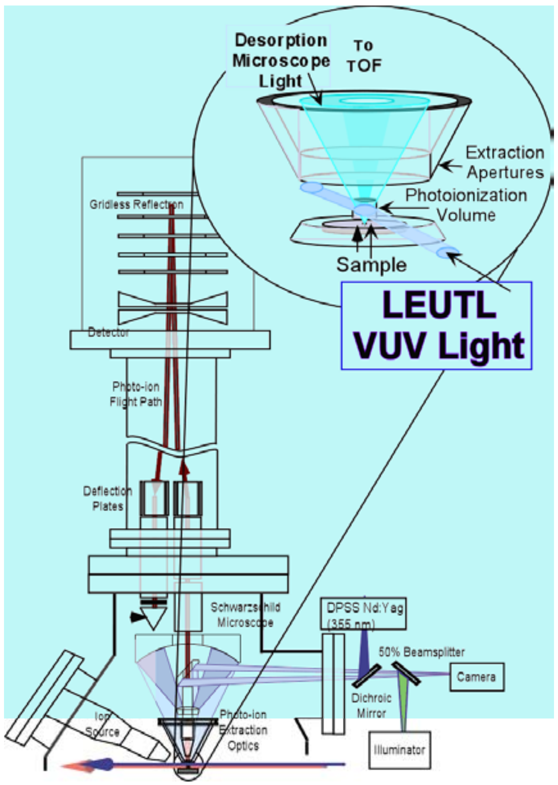




LEUTL

The First APS FEL Experiment

Single-Photon Ionization / Resonant Ionization to Threshold (SPIRIT)



Coming 2002

M. Pellin MSD/ANL

SPIRIT will use the high VUV pulse energy from LEUTL to uniquely study –

- **Trace quantities of light elements**:
  - H, C, N, O in semiconductors with 100 times lower detection limit
- **Organic molecules <u>with minimal fragmentation</u>**
  - cell mapping by mass becomes feasible
  - polymer surfaces
  - modified (carcinogenic) DNA
  - photoionization thresholds
- **Excited states of molecules**
  - cold wall desorption in accelerators
  - sputtering of clusters

Time-resolved measurement on the SASE FEL

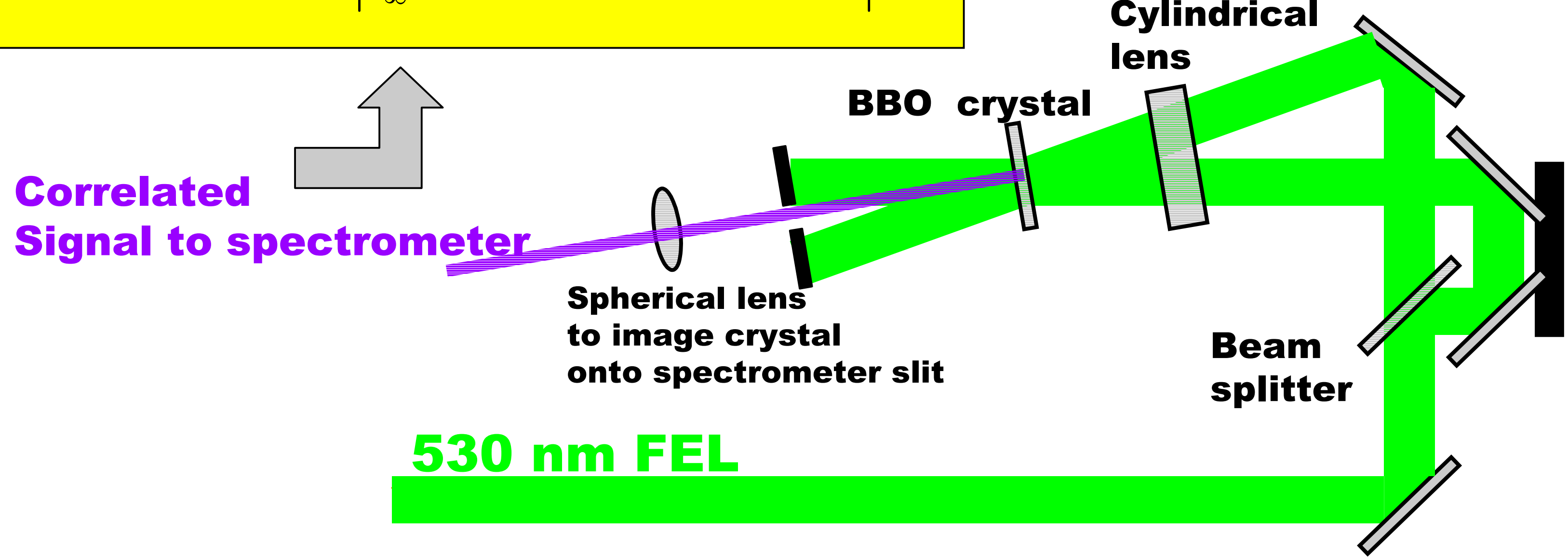
FROG = Frequency Resolved Optical Gating

For the second harmonic FROG

$$E_{sig}(t,\tau) \propto E(t)E(t-\tau).$$

And the measured signal on the spectrometer is

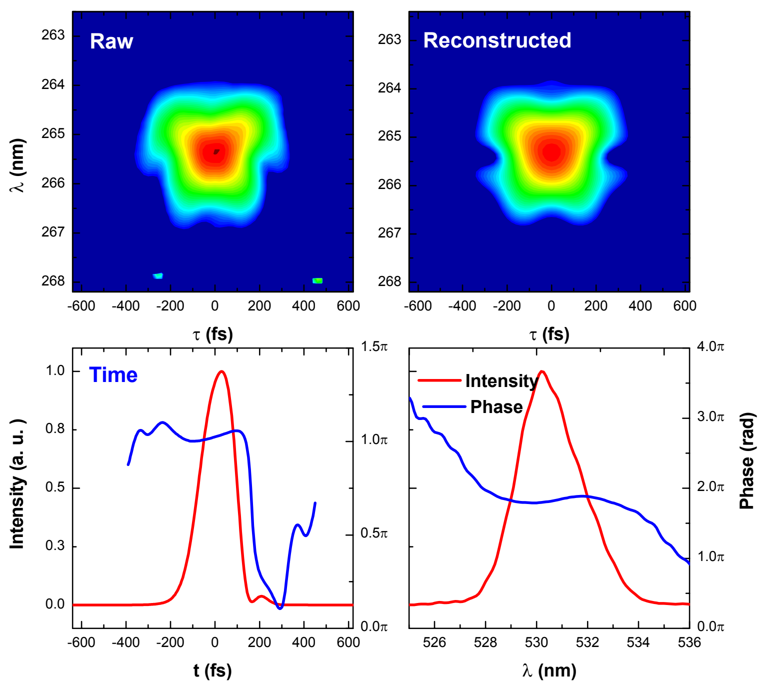
$$I_{FROG}(\omega,\tau) \propto \left| \int_{-\infty}^{\infty} E_{sig}(t,\tau)\exp(-i\omega t)dt \right|^2 .$$



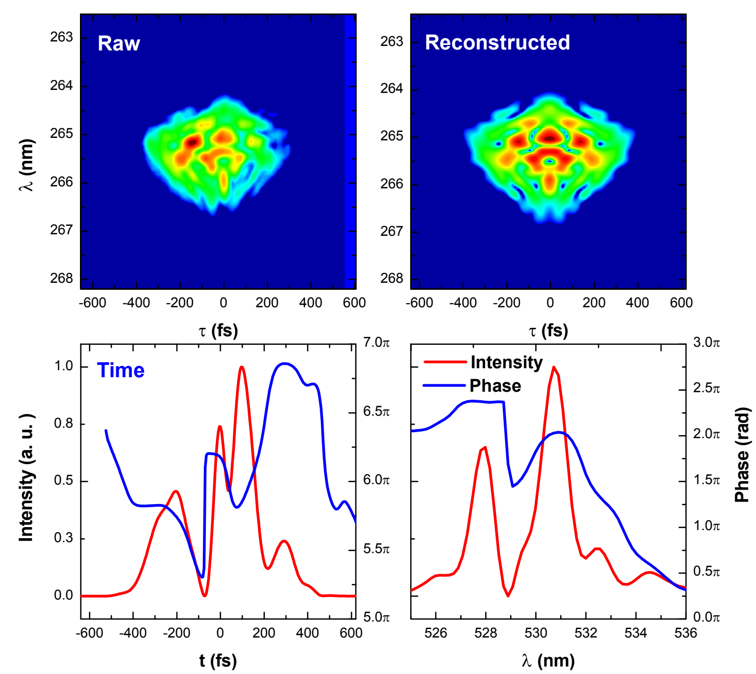
Y. Li

FROG examples

FROG sample 1



FROG sample 2



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Observation of the intrinsic chirp and the imprint of the Electron beam energy chirp

[PRL 89, 234801 (2002)]

The FEL output is

$$E(t,z) = E_o(z)\sum_{j=i}^{N_e} \exp\left[i\omega_0[1 + c\frac{\sigma_\delta}{\sigma_z}(t - t_0)](t - t_j) - \frac{(t - t_j - z/v_g)^2}{4\sigma_t^2}(1 - \frac{i}{\sqrt{3}}) \right].$$

The total chirp in the pulse is

$$\phi'' = \frac{d^2\phi}{dt^2} = 2\frac{\Omega\Theta + \Phi''_m}{\Omega^2 + \Phi''^2_m},$$

where

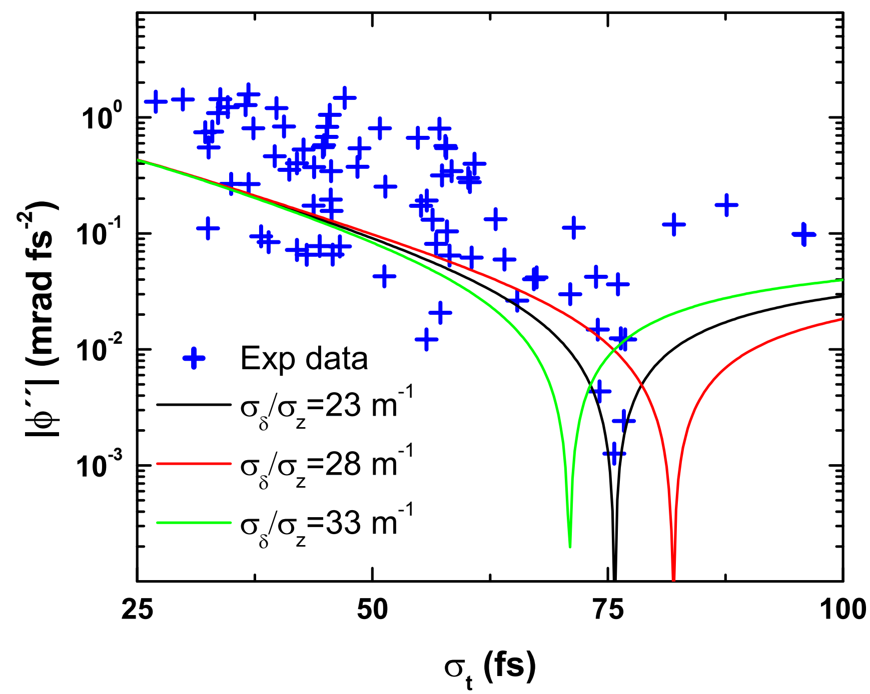
$$\Theta = \frac{1}{\sqrt{3}} + 4\sigma_t^2\omega_0 c\frac{\sigma_\delta}{\sigma_z},$$

$$\Omega = 4\sigma_t^2 + \Phi''.$$

σ_t: coherence length

Φ_m'': group velocity dispersion in optics

σ_δ/σ_z: electron beam energy chirp



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Other topics (partial)

- Midwest Accelerator Physics collaboration
- Linear coupling of RMS emittance (L.Teng)
- Electron cloud: beam-induced multipacting resonance (K. Harkay with undergrad student L. Loiacono)
- CSR microbunching at SURF (K. Harkay with NIST, N. Sereno, and K-J. Kim)
- Beam halos (S. Milton with grad student D. Huang)

Summary

- AP Group pursuing accelerator physics R&D in a number of areas
- Highest-priority topics address near-term anticipated User requirements
- Also pursuing general accelerator physics topics and far-term light source development